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VENUS

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16. Abstract

Recent investigations of the planet Venus are reviewed on the basis of a wide survey of domestic and foreign literature. The individual topics examined include the configuration and seasons of the planet, its mass, radius, rotation, internal structure, magnetic field, captured radiation belts, photometric properties and optical parameters, radio temperature and thermal and dielectric properties of the surface, composition of the Venusian atmosphere, spectral observations above the cloud layer, the composition of the lower Venusian atmosphere from Venera-4 data, the physical conditions below the cloud layer, etc.

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In three years (1967-1969), our knowledge of Venus finally /19* was given a firm foundation. The period of rotation of the planet about its axis was defined; the position of the axis of rotation was reliably established; the radius of the planet was measured. However, the greatest achievement has been the direct investigation of the planet by means of the Venera 4, 5 and 6 spacecraft, which performed direct measurements in the atmosphere of Venus, allowed us to determine the chemical composition, pressure and temperature in the lower layers of the atmosphere, thus creating a reliable basis for all subsequent studies of Venus -- both terrestrial and those performed by means of spacecraft.

But before going over to a presentation of new results, it would be useful to recall briefly that which was known concerning Venus before 1966 and early 1967, utilizing reviews [5, 18, 26].

Venus is the planet closest to us in the solar system and the brightest object in the sky after the sun and the moon. The mean distance of Venus from the sun is 0.723 a.u. (108.1 million km.); the period of rotation around the sun is 224.7 days.

The radius of Venus is near 6000 km., its mass is about 80% of that of the Earth. The mean density of the planet is 5.2 g/cm^3; the acceleration of the force of gravity on the surface is 880 cm/sec^2.

These figures are similar to the corresponding values for Earth and gave rise to the belief that conditions on Venus also would not differ greatly from those on Earth. The presence of an atmosphere on Venus, discovered in 1761 by M. V. Lomonosov as he observed the passage of Venus across the disc of the sun, strengthened this conviction still more.

However, it was found to be impossible to discover any details on the surface of the planet; from time to time experienced observers could note only long, low-contrast details on the surface of the planet -- most probably clouds. Photographs in UV-rays showed more stable formations, also clearly of atmospheric origin. No details of the surface of the planet could be detect- /20 ed, making determination of the period of rotation and inclination of the axis of rotation of the planet to the plane of its orbit most difficult.

*Numbers in the margin indicate pagination in the foreign text.

Only the use of radar methods allowed us to determine that the period of rotation of Venus is near 243 days, that the direction of its rotation is retrograded, while the direction of the axis of rotation is near perpendicular to the plane of its orbit.

By 1932, spectroscopic studies had detected CO in the atmosphere of Venus. However, the spectroscopic data did not allow scientists to determine the total quantity of CO_2 in the Venusian atmosphere. The problem is that the CO_2 lines are formed not in a pure gas atmosphere, but rather in the cloud layer, the structure and extent of which were unknown. The dimensions and optical properties of the particles of which the clouds are made were also unknown. In addition to CO_2, traces of CO, H_2O, HCl and HF were observed in the atmosphere of the planet.

Determination of the temperature on the surface of Venus was very difficult. The equilibrium temperature of Venus, at which the quantity of energy received from the sun is equal to the quantity of energy lost due to thermal radiation, is 238 K. Measurements of the infrared radiation of Venus indicated a similar value (on the order of -40° C). However, measurements of the radio temperature of Venus at λ = 3 cm, performed first in the USA in 1956, indicated a value of $\sim$600 K. Since that time, many measurements in the range from 3 mm to 70 cm have shown that in the range λ = 3-30 cm, the radio temperature is constant and equal to $\sim$600 K, while in the range shorter than 3 cm it decreases and at λ = 3 mm it is equal to 300 K. The temperatures of the day and night hemispheres of Venus have been found to be approximately equal.

The great temperature difference in the centimeter and decimeter ($\sim$600 K) and millimeter wave bands (300 K) can be explained by the assumption that the radiation at longer wave lengths (λ>3 cm) for which the atmosphere of Venus is transparent, originates at the surface of the planet, whereas the radiation in the millimeter wave band, for which the atmosphere is partially opaque, originates at some level of the atmosphere with a lower temperature. However, this assumption requires that some powerful surface-heating mechanism be found.

The difficulty in selecting suitable mechanims of heating resulted in the development of alternative hypotheses, relating the high temperature and spectrum of radio radiation of the planet to the existence of a hot-dense Venusian atmosphere; high radioactivity of the surface, maintaining the atmosphere ionized, the formation of radiation due to discharges in the atmosphere consisting of CO_2 and other hypotheses were set forth (for example, see [5, 26, 84, 146]).

The results produced by the Mariner 2 spacecraft tilted the balance in favor of the hypothesis of a heated surface. In /21

December of 1962, Mariner 2 flew by Venus at a distance of about 30,000 km; the disc of the planet was scanned three times by radiation sensors operating at λ = 1.35 and 1.9 cm; on the light and dark sides of the planet, and once across the terminator. At λ = 1.9 cm, a decrease in intensity was noted toward the edges of the disc, which is difficult to explain within the framework of the ionospheric hypothesis.

These were the main conceptions of Venus which had been accumulated by 1966. Extensive data were available on the spectrum of Venus in the visible and infrared areas, the radio radiation of the planet over a rather broad range of wave lengths; the period of rotation of Venus had been determined. However, there were essentially no reliable data on the planet below the cloud layer.

Due to this, many published models of the Venusian atmosphere were necessarily based on various indirect considerations concerning the composition of the Venusian atmosphere and the pressure at the surface.

For example, Moroz in his monograph "Fizika Planet" [The Physics of the Planets], published in 1967 [26], based on the data published up to that time, including the results of experiments on Mariner 2, calculated a model of the atmosphere of Venus on the assumption that the mean molecular weight of the atmosphere was 28, for three sets of parameters (p_0 and T_0 are the pressure and temperature at the surface):

p_0 = 30 atm T_0 = 500 K (minimal model)
p_0 = 23 atm T_0 = 600 K (mean)
p_0 = 40 atm T_0 - 700 K (maximal model)

In order to determine the true conditions on the surface of the planet, new methods of direct measurment of the atmosphere of Venus below the cloud layer were required. This great scientific problem was successfully solved by the Soviet automatic interplanetary spacecraft Venera 4, 5 and 6, which entered the atmosphere of Venus and landed on the surface of the planet and transmitted data on the temperature, density and chemical composition of the deep layers of the Venusian atmosphere. The measurements of the Soviet spacecraft showed that the content of CO_2 in the atmosphere of Venus is 97%, the content of O_2 is not over 0.1%, the quantity of H_2O in the atmosphere, within the limits of the altitude interval of measurements, is 0.6-10 mg/l, the content of N_2 plus inert gases is not over 2%. The temperature of the surface of the planet reaches 500° C, the pressure is on the order of 100 atm.

Let us now go over to a more detailed presentation of the results of the studies of Venus in 1967-1969.

1. The Ephemeris and the Value of an Astronomical Unit /22

Before the radar studies of Venus, the most precise value of an astronomical unit was the value produced by Rabe from analysis of optical observations of the asteroid Eros: 149,504,000 ± 17,000 km. The radar studies of Venus allowed the accuracy of definition of the a.u. to be increased significantly, and in 1964 the Twelfth General Assembly of the International Astronomical Union recommended that the radar value of the a.u. be used in astronomical annuals.

The accuracy of measurement of distances by radar achieved to date is 1-2 km (ignoring the error in the value used for the speed of light). The value of 1 a.u. defined by measurements in the USSR in 1961-1964 agrees well with measurements made in the USA and England at 149,598,000 km ± 130 km (mean square error including inaccuracy in the value of the speed of light) (32, 136].

However, radar measurements performed in the USSR and the USA in recent years have shown that even after a correction is introduced to the value of the astronomical unit used, there are still significant divergences between actual and calculated positions of Venus in orbit in relationship to the Earth. Most of the differences, which reach several hundreds of kilometers, can be eliminated by assuming that the difference in heliocentric longitudes of Venus and the Earth differs by 0.5 sec. From the ephemeris value calculated from the analytic theory of Newcomb considering the corrections of Dancomb to the elements of the orbit of Venus [32].

2. The Configurations of Venus and the Time of Year

Venus is an internal planet, and its configurations are limited by the conjunctions (upper and lower) and elongations (western to eastern; greatest elongation not over 47°).

Anomoly of dichotomy. Long ago, a peculiarity was noted which occurred at the point of the dichotomy -- the moment when the phase of the planet is precisely equal to 1/2. Since the motion of the planet in its orbit has been calculated with high accuracy, it is possible to calculate the moment of dichotomy with equal accuracy. Actually, the error in these predictions reaches several days, the dichotomy occurring in the eastern (evening) elongation long before the predicted moment, and always occurring late in the western (morning) elongation. Thus, according to the observations of Robinson in 1963 and 1964 [154], the dichotomy in the morning elongation was 4.5 and 5 days late; according to the /23

observations of Dujnic [85] in November 1965 thru March 1966, the dichotomy occurred on 10 November 1965 -- 5 days earlier than the ephemeris time. According to a number of reports, a correlation of sorts has been observed between the deviation of the actual moment of dichotomy from the predicted moment and the level of solar activity, although Sandner [161], noting a delay of the dichotomy in the eastern elongation of 1-14 days (averaging 5.6 days) with a lead in the morning elongation of 2-12 days (averaging 4.8 days), noted no correlation with solar activity. The results of Sandner were confirmed by the work of Ahnert [46]. Lozitskiy [22], observing Venus through a 60 mm refractor in three elongations, found a mean difference in moments between the moments of the observed and predicted dichotomy of ~6.5 days, this difference being approximately half as great in absolute value in the western elongations as in the eastern.

Chambers and Taylor study the anomoly of the phases of Venus [66] and confirmed the existence of the effect of straightening of the terminator detected by Bronshtein in 1934.

Seasons. Calculations of the seasonal changes on Venus were published by Brooks [63]. According to Brooks, the mean duration of a season on Venus (56 Earth days) is approximately equal to 1/2 the duration of the Venusian day (58.5 Earth days).

Due to this, each of the seasons should come at approximately the same time of the Venusian day for an extended period of time. The seasonal effect might be produced due to differences in height of the sun during the course of the Venusian day, although the slight inclination of the equator of Venus to the plane of its orbit (<10°) sharply reduces the seasonal effect.

3. Mass

Speaking at the Twelfth General Assembly of the International Astronomical Union (Hamburg, 1964), G. Clemence [67] stated that the accepted values of the masses of the large planets doubtless need refinement. However, at present it is undesirable to change the accepted masses of the planets, since these values satisfy the task of predicting the ephemeris with an accuracy sufficient for most practical purposes. Nevertheless, determination of the masses of the interior planets is a very pressing problem, particularly in connection with the requirements of trajectory problems for the calculation of close passages or landings of spacecraft.

Venus has no natural satellites, and until recently the only means for determining its mass was observation of the perturbations produced by the attraction of Venus in the motion of the other planets, particularly the Earth. At the present time, this

rather inaccurate method has been replaced by measurements of the trajectories of spacecraft flying past the planet by means of radiometers. /24

Thus, when the Mariner 5 spacecraft flew past Venus, its distance and velocity were determined by the time delay of the signal and the Doppler shift of the signal frequency respectively. Processing of the measurements produced the value of the product of the gravitational constant times the mass of Venus M [67]:

$$GM = 324,859,61 \pm 0.49 \text{ km}^3/\text{sec}^2.$$

Taking the value of an astronomical unit as

$$1 \text{ a.u.} = 149,597,890 \text{ km},$$

we find that the ratio of the mass of the sun to the mass of Venus is

$$408,522.6 \pm 0.6$$

Processing of the trajectory measurements of Mariner 5 by Anderson, Efron and Pease [51, 52] yielded a similar result:

$$408,523.10 \pm 0.24.$$

4. Radius and Figure

Venus is covered by a solid cloud cover, impenetrable throughout the entire optical wave band. Therefore, the classical optical methods of determination of the radius of the planet give us essentially the radius of the cloud cover, not the radius of the solid body of the planet.

According to the estimate of Vaucoulers [179], the radius of the cloud cover is 6120 ± 7 km; Martynov [23] estimated a value of 6100 ± 30 km. Returning to the problem of determination of the radius of Venus, Martynov [24] emphasized that determination of the radius of Venus at the level of the cloud cover involves great error (±25-30 km) leading to low accuracy of the determination of the height of the Regulus cover over the cloud layer. According to [24] this height over the surface of the planet is 133 ± 10 km.

New optical measurements of the radius of Venus were made by Dollfus [83] using a dual-image micrometer. For the radius of the upper layer of clouds he produced a value of 6110 ± 15 km, for the radius of the layer of particles suspended in the upper layers of the atmosphere of Venus -- 6150 ± 20 km. Considering the data of Venera 4 and Mariner 5, as well as radar data, Dollfus estimated that the upper boundary of clouds corresponds to the level of the tropopause and an altitude of 56 ± 20 km [8].

Basically new capabilities for determination of the radius of the planet were provided by the invention of radar. Radar devices send out a pulse of radio waves, which reach the surface of the planet, are reflected from it and return. Obviously, at a sufficiently great distance the leading edge of a pulse can be considered a plane. The pulse reaches the subterral point (the point closest to the Earth) of the planet first and is reflected from it, after which reflection occurs from a circular zone with its center in the subterral point; the distance from the points of this zone to the radar antenna is identical. The width of the zone is determined by the pulse length, and its radius increases as the pulse continues to propagate, until it reaches the radius of the planet; after this, reflection stops. /25

Analysis of the time delay of reflection of a pulse allows us in principle to determine the radius of the planet, if all parameters determining the pulse delay are known with sufficient accuracy (including, in particular, the precise ephemerides of the Earth and the planet being studied).

Using a similar method, work on determination of the radius of Venus was performed by the jet propulsion laboratory. During processing of the results of measurements by integration of the equations of motion of the bodies of the solar system, corrections were produced for 10 parameters significant for measurements by the time-delay method. The results produced were as follows [31]:

Radius of Venus	6,053.7	2.2 km
1 a.u.	149,597,892.9	5 km

The radius of Venus was also determined by observation of a fly-by of Venus by the Mariner 5 spacecrafte [111]. The center of mass of the planet was the focal point of the hyperbolic (relative to Venus) trajectory of the flight of the spacecraft, and its position could be determined by trajectory measurements. The position of the nearest surface area was measured using the 300-meter radar antenna at Arecibo (Puerto Rico). These calculations indicated a value of 6054 km for the radius of Venus.

This determination was put somewhat in doubt after correlation of the results of measurements performed by Venera 4 and the trajectory measurements of Mariner 5 indicated a value for the radius of Venus of 6085 ± 10 km [27]. However, combined processing of all radar data, as well as meridianal observations of Venus performed by the United States Naval Observatory in 1950-1965 have indicated a value of 6050 ± 0.5 km [53]. Combined analysis of radar determinations of the radius of Venus and trajectory measurements of Mariner 5 [50] indicated a value for the radius of Venus of 6052 ± 2 km; the correction to this value to consider the delay

of the signal in the atmosphere, for which a pressure at the surface of 100 atm was assumed, with a temperature of 800 K, is + 0.3 km.

In conclusion, we present a summary of the determinations of the radius of Venus from review [8] (see Table 1): /26

TABLE 1. RADIUS OF THE SURFACE OF VENUS

Measurements	Year of Publication	Radius, km	Method of Measurement
Physics Institute, Acad. Sci.	1965	6057±55	Radioastronomical
Lincoln Laboratory	1967	6076±1	Processing of radar data from 1961-1966
Institute of Radio and Electronics	1968	6046±15	Radar
Lincoln Laboratory	1968	6048±1	"
Arecibo	1968	6052±2	"
JPL	1968	6053±2,2	
"	1968	6052,5±2,5	Mariner 5 trajectory measurements and radar

Using the trajectory measurements of Mariner 5, Anderson, Efron and Pease [51] estimated the value of the zonal harmonic J_2 of the gravity field of Venus; its value was found to be $(8.4 \pm 3.9) \cdot 10^{-6}$. This indicates that Venus has very little polar flattening -- on the order of ~1/100 that of the Earth.

A report by Smith, Shapiro, Esha and Ingols at the symposium "The Atmosphere and Surface of the Moon and the Planets" (Woods Hole, USA, 1969) presented the results of radar measurements of the figure of Venus and the altitude profile of the surface. In the equatorial plane, the cross section of the surface is approximated by an ellipse, the difference in the semi-axes of which is 1.1 ± 0.35 km. The semi-major axis of the ellipse makes an angle of 55° (clockwise) with the direction toward the Earth at the inferior conjunction. The center of mass is displaced relative to the center of the figure by 1.5 ± 0.25 km in a direction of 15° relative to the direction toward the Earth at the inferior conjunction [8].

5. Rotation

For a long time, determination of the period of rotation of Venus was a difficult problem for observational astronomy. The

solid cloud cover over the planet made it impossible to observe any details of the surface in the IR,UV or visible range of the spectrum. The details which could be observed, which were used to calculate periods of dozens of hours up to 224.7 days (with Venus always turning the same hemisphere toward the sun), in both the forward and retrograde directions, related clearly not to the surface but rather to the atmosphere of the planet, and essentially indicated only that strong dynamic processes were occurring in its atmosphere. /27

Only the use of powerful radar equipment in combination with frequency analysis of the pulses returned allowed reliable determinations of the period of rotation of Venus and the position of its axis of rotation to be made.

In principle, the determination of the period of rotation of the planet was based on the Doppler frequency shift of the signal reflected from various sections of the disc of the rotating planet. On any rotating body, the lines of constant ray velocity (and consequently, Doppler shift) are projected as straight lines parallel to the axis of rotation. On a straight line passing through the center of the disc, the Doppler shift is equal to zero (if we consider the relative orbital motion of the radar antenna and Venus). The ray velocity increases as we approach the limb. Therefore, the spectrum of a returning signal expands until reflection occurs from the very limb of the planet, after which the spectrum breaks off. By measuring the width of the base of the spectrum as a function of date (assuming that reflections continue out to the limb), we can determine the direction and period of rotation of Venus.

The angular velocity of Venus observed from the Earth represents a projection onto the sky of the sum of two rotation vectors: one of these corresponds to the rotation of Venus about its axis, the other -- to its apparent rotation due to the relative motion of Venus and the Earth. If Venus had forward rotation around its axis and its axis of rotation were approximately perpendicular to the plane of the ecliptic, the two vectors would be added and would yield the maximum width of spectral base near the conjunctions. If the rotation of Venus were retrograde, the two vectors would be subtracted near the conjunction, yielding the minimum spectral base width. Of course, any measurement yields only a projection of the angular velocity, not the true value, but by tracing changes in the measured angular velocity with time we can determine the true value. This requires that computers be used to analyze the frequencies of the returning signals.

Determinations of the period of rotation and position of the axis of rotation of Venus at Goldstone (1964) yielded the following results [28]:

Period	250 ± 6 days (retrograde rotation)
Coordinates of the North Pole	α = 255 ± 3.4°; δ + 68 ± 2.7°
Inclination of the axis of rotation relative to the plane of orbit	~9°

The discovery in the spectrum of the reflected signal of peculiarities shifting in frequency with the rotation of the planet about its axis allowed them to be identified with details on the surface of the planet, which allowed the measured values of the period of rotation to be refined still further. /28

A great deal of work on the determination of the periods of rotation of Mercury and Venus by the radar method has been performed at Arecibo by means of the 300-meter radiotelescope operating at λ = 70 cm [86]. Observations over a period of 3 months at the lower conjunction in 1964 indicated that the synodic period of rotation of Venus is 117 ± 0.7 d, the siderial period is 245.1 ± 0.7 d (retrograde rotation). The axis of Venus is projected onto the sky at a point with coordinates δ = -66.7 ± 0.4°; α = 90.3 ± 0.1°. The inclination of the axis of rotation to the ecliptic is -89.8 ± 0.4°, to the orbital plane -86.7 ± 0.4°.

Shapiro, et al [164], have provided us with a systematic presentation of the method used to determine the periods of rotation of Mercury and Venus. He presented a formula for determination of the vector of rotation of near-spherical bodies and studied the influence of the rule of scattering of the surface of the planet, the duration of an impulse and the characteristics of the radar system on the period defined. According to Shapiro, introduction of these corrections might slightly decrease the directly measured period of rotation of Venus, but would make practically no change to the measured period of rotation of Mercury.

During the period between two inferior conjunctions, Venus makes 4 complete rotations in relation to a terrestrial observer. The sidereal period of each rotation (retrograde) is 243.16 d.

Comparison of the results of radar observations of Venus made with the 26-meter radiotelescope at Goldstone [65] and data from measurements made in 1962 and 1964 indicates a stellar period of Venus of 243 ± 1 d, corresponding to a period between opposition of 243.16 d. This means that at each opposition, Venus turns the

same side toward the Earth. Goldreich and Peale also concluded that the sidereal rotation of Venus was quite close to the "resonant" value for the relative orbital motion of the Earth.

After analyzing the results of various radar determiantions, Shapiro [165] concluded that the plane of the equator of Venus is inclined to the plane of its orbit by not more than 2.2°. The sidereal period is equal to 243.09 ± 0.18 days, which is quite close to the "resonant" period of 243.16 days. Analysis of this motion shows that the tidal effect might cause oscillations in the period of rotation of ∿0.01 days, with a period of 58.5 days.

Goldreich and Peale [91] explain the "resonant" nature of the rotation of Venus by the tidal influence of the Earth on Venus, the figure of which should have triaxiality similar to that of the moon. /29

The problem of spin-orbital interactions in the solar system was discussed by Goldreich and Peale in more detail in [92], dedicated to the possibility of conversion of the planets to a state of stable resonant motion. In their opinion, tidal friction caused by the sun cannot in itself provide the necessary condition for a transition to a state of stable resonance. Resonant capture can be explained by assuming that Venus has a liquid core like that of the Earth. Capture is most probable if the core is coupled with the mantle so that it reacts to a change in rate of rotation in $3 \cdot 10^4$ years. A study of the nature of the gravitational field of Venus could in principle be used to determine the direction and speed of the initial rotation of the planet.

An attempt to explain the unusual (long-period retrograde) rotation of Venus was undertaken by Boneff and Sadovski [57, 58]. Based on cosmogonic considerations, the authors believe that all of the planets originally had retrograde rotation, which was later converted to forward rotation for most planets due to tidal interactions in the solar system; Venus has simply retained its initial retrograde rotation.

In conclusion, we should note that in recent years, intensive observations of Venus in ultraviolet light, in which faded, low-contrast spots can be observed, have indicated a period of retrograde rotation of ∿4 days [75, 153].

The discovery of this period stimulated Smith [171] to turn his attention to the existence of a contradiction between the radar period of rotation of 244.3 ± 2 days and the period of 4.7 ± 2 days determined by observation of spots in UV on the disc of Venus.

Answering Smith, Shapiro [166] noted that the firmly established period of ∿243 days relates to the solid surface of the planet, whereas the period of ∿4 days clearly relates to the motion of clouds at ∿100 m/sec, which is comparable to the speed of winds in the stratosphere of the Earth.

6. Internal Structure

The dawning of the space age has stimulated a rapid increase in work on the investigation of the internal structure of the planets, considering the accumulated experience of the study of the internal structure of the Earth by means of geophysical methods. In this respect, Venus is a rather convenient object for investigation, since its mass and dimensions are similar to those of Earth.

In constructing models of the Earth, seismic data are important, i.e. data on the propagation of powerful elastic waves through the Earth. These data allow us to relate the elastic constants of the material of the Earth to density, which in turn allows us to produce an equation of state of the matter of our planet and construct a distribution of density with depth, determine phase transitions, changes in chemical composition, etc. Studies of the moon by this method have already begun -- the first seismometer has been installed on the moon. As concerns the terrestrial-group planets, the position is complicated by the fact that the elastic properties of the these planets are not as yet known. Therefore, in order to construct models of these planets we must use the eqution of state of matter of the Earth, produced in geophysics, and the equation of state of iron, determined in high-pressure physics. /30

The calculation of the internal structure of the terrestiral planets performed by Bullen [64] approximately by this plan led him to the conclusion that the core of Venus is a result of a phase conversion of matter and that the liquid core of Venus should be smaller than that of the Earth.

Establishment of the fact that Venus has practically no magnetic field has led to a number of interesting conclusions concerning the internal structure of the planet. For example, Hedervari [101], calculating the internal structure of Venus and Mars in 1963, concluded that in Venus at a depth of 3800 km a pressure of 1.4 million atm is reached, corresponding to the transition from the mantle to the outer core of the Earth. However, on Venus the pressure corresponding to the Leman zone[1] and the transition

[1] Here we should clear up one misunderstanding. The conversion from the outer core of the Earth to the inner core was discovered by I. Leman, the female geophysicist.

to the inner core is never reached. Based on the assumption that magnetism is explained by processes in the inner core, not in the outer core, Hedervari concludes that Venus should have no magnetic field. Based on the absence of a magnetic field of Venus, Runcorn [155] concluded that Venus has no liquid core.

The firmly established fact of the high surface temperature of Venus (~500° C) leads to curious results concerning the composition and strength of the upper lithosphere of Venus. The fact is that all rocks are fully dehydrated and their bending and rupture strength greatly reduced at this temperature.

As a result, even if the mean chemical composition of the Earth and Venus are identical, processes of differentiation of magma and isostatic equilibration would occur quite differently on /31
Venus, leading to differences in the surface relief. In particular, due to the difference in the conditions of isostatic equilibration, we should expect that Venus would not have any deep "roots of mountains." Since it is quite probable that erosion processes occur on Venus, the planet apparently has only a small number of high peaks, significant features of a generally horizontal topography.

Responding to the hypothesis of Davidson and Anderson [76], according to which the nontransparency of the atmosphere of Venus is explained by the expulsion of dust from volcanoes (about 10 per year), Weertman [183] estimated the possible tectonic activity of Venus and concluded that it should be significantly less than that of Earth. He based his conclusion on the assumption that the temperature gradiants in the crust and upper mantle of Venus and the Earth are the same and that the upper mantle of both planets has identical composition. Since the temperature of the surface of Venus is 200-300° higher than that of the Earth, the depth of deposition of the layer of reduced viscosity on Venus must be 125-130 km. Then, convection flows in the mantle might be mechanically separated from the crust, decreasing tectonic activity.

7. Magnetic Field and Radiation Belts

Until spacecraft were sent to Venus, the existence (or absence) of a magnetic field of Venus could be determined only by various indirect methods.

In particular, Jeffries [112] indicated the possibility of estimating the intensity of the magnetic field of Venus on the basis of the intensity of its glow, on the assumption that this glow is caused by streams of charged particles deflected by the magnetic field, as is the case for the polar aurora of Earth.

Magnetic field measurements by Mariner 2 did not indicate any noticeable magnetic field of Venus [26]; however, the range of passage of the spacecraft from the planet did not allow a definite conclusion to be drawn.

Reliable measurements of the magnetic field in the neighborhood of Venus were made by Venera 5.

Using a three-component ferromagnetic probe magnetometer, Venera 4 measured the magnetic field of the planet during the close approach phase of the trajectory (31,000-200 km from the surface) [17]. The range of measurements for each component was ± 50 γ, the resolving capacity ± 1.6 γ. The measurements showed that Venus has no significant dipole field; its magnetic moment is not over 1/3000 that of the Earth.

Mariner 5 carried a three-component magnetometer with a noise level of 0.1 γ. There was also a plasma detector, which recorded the flux of positive ions in 32 energy intervals between 40 and 9400 eV. /32

The results of the measurements showed that before the approach to the planet and after passing the planet, the interplanetary field was moderately perturbed ($H \approx 8$ γ). Upon approach to the planet, passage through a shock wave ($H \approx 15$ γ, direction close to direction toward sun) was recorded. The field then dropped suddenly to about 6 γ and became less than the interplanetary field; the fluctuations in the field increased significantly, although the direction did not change. As the spacecraft flew further, it once more passed through a shock wave, after which the ordinary conditions of the interplanetary field were restored [62].

A second experiment, performed on Mariner 5 [47], included 3 Geiger counters and a crystal detector with four levels of radiation. Mariner 5 passed Venus four times closer than Mariner 2, but no increase in the flux of particles near Venus was recorded. This indicates that the upper level for electrons with $E_e > 45$ KeV is 3.0 particles/cm^2·sec·ster; for protons with $0.32 < E_p < 12$ MeV, 1.0 particle/cm^2·sec·ster. Processing of the measurement data from Mariner 5 using the data of two independently operating magnetometers led to estimates of the magnetic moment of Venus of 1/2000 [62] and 1/1000 [47] of the magnetic moment of Earth.

However, the two experiments agreed with each other in their indication of a perturbing influence of the planet on the interplanetary medium: for example, Venera 4 crossed a shock wave at distance of 28,000 km from Venus [17].

Comparison of the magnetograms of Venera 4 during the approach sector with the magnetograms of Mariner 5 over the same time interval when Mariner 5 was located some $0.48 \cdot 10^6$ km from the planet indicated [16] that the magnetic field observed by Venera 4 is the solar interplanetary field. This explanation is based on the observation of a 27-day repetition cycle of the magnitude and direction of the interplanetary magnetic field, as well as the repetition of characteristic features of the field on magnetograms recorded by both spacecraft, in spite of a certain difference in the absolute levels of the field. The analysis indicates that the magnetic field observed by Venera 4 in the immediate vicinity of Venus -- at a range of from 200 km to its surface -- is the interplanetary solar field, amplified and turbulized by passage through the shock wave. The available estimates of the magnetic dipole moment of the field of Venus can be reduced to values of $<10^4$ of the terrestrial field [16].

Since Venus has no magnetic field, it also has no belts of captured corpuscular radiation. The indications of low-energy charged-particle counters on Venera 4 and Mariner 5 showed no significant changes in the flux of particles throughout the entire flight. Upon transition into the geometric shadow of Venus, the counting rate dropped, but still remained over 1/2 its previous rate. This indicates that there are secondary particles generated by bombardment of the upper layers of the atmosphere of Venus with cosmic rays [21]. /33

8. Photometric Properties and Optical Parameters of Venus

The most important optical methods of investigation of the atmosphere are polarimetry, radiometry and photometry (or colorimetry with narrow-band filters).

Photometry. Extensive work on multicolor photoelectric photometry of the bright planets has been performed by Irving, Young, Simon, et. al. [107-109, 187]. Observations were performed using a 16-inch cassegrain telescope at Boiden Observatory (UAR) and a 12-inch telescope (southern France) in twelve narrow areas of the spectrum between 3150 A and 1.06 μ, and also in the U, B, V system. The results of the investigations indicate [107] that the Bond albedo for Venus is 0.77 ± 0.7, and that forward scattering in the atmosphere is less pronounced than earlier assumed; the spectral reflectivity depends strongly on phase angle: Venus becomes bluer at higher angles.

However, Starodubtseva [36] noted that at the current level of error it is impossible to determine the optical parameters of Venus from the data of relative surface photometry at phase angles $>60°$.

In 1969, Starodubtseva [37] published results of spectrophotometric comparison of individual areas of Venus. The observations were conducted on the 70-cm reflector of the Ukranian Academy of Sciences Observatory with a dispersion of 30 A/mm. The influence of atmospheric dispersion on the distribution of brightness in the spectrum was studied with various orientations of the slit relative to the limb and the terminator. It was shown that the drop in brightness toward the violet end of the spectrum can be explained to a great extent by atmospheric dispersion. In the opinion of Starodubtseva, the visible surface of Venus is spectrophotometrically homogeneous when no dark details are present. The spectrum of the dark details shows a drop in the intensity toward the short-wave end of the spectrum.

Sislov and Shukurov determined the albedo of Venus in the UV area of the spectrum by a photoelectric method [43]. The observations were conducted in the autumn of 1967 at El'brus with a telescopic photometer with a quartz lense. The optical system was based on the Fabry plan; the receiver used was a type FEU-18 A photomultiplier. The mean albedo for λ = 3130 A was 15 ± 1%, for λ = 3995 -- 23 ± 2%.

Abhyankar [45] attempted to explain the excess brightness of /34
Venus at phase angles of over 120° by diffusion of the visible radiation in the spherical atmosphere of the planet. Using the data of Venera 4 and Mariner 5, he concluded that the Rayleigh scattering of radiation in the atmosphere produces only a portion of the excess brightness. The remaining excess radiation must be attributed to scattering in the aerosol layer 15-20 km thick at an altitude of ∿40 km.

Polarimetry. In 1959-1968, Coffeen and Gehrels [68, 69] measured the polarization of the light of Venus in 9 wave lengths in the 3400-9000 A interval by a photoelectric method using a Wollaston polarimeter with filters. The measurements were conducted using various instruments with apertures of 53-208 cm. The results of the experiment were summarized in a catalogue of ∿500 measurements of the degree and angle of polarization, covering phase angles of 7-160°. The polarization angles have sharp peaks of the distribution near 90 and 180° (±5°).

The authors studied the course of polarization with phase for various wave lengths and the change of polarization with wave length for various phase angles, as well as the distribution over the disc. In UV-rays at low phase angles, the polarization is positive, at angles of >15° it becomes negative. At a phase of 90°, the maximum polarization in UV occurs at the ends of the crescent (∿18%); in IR, the picture is the reverse, indicating different mechanisms of scattering for UV and IR. In UV, polarization changes with time, while at longer wave lengths it is constant.

Later, the observations were compared with calculations for various light scattering mechanisms [68]. Rayleigh scattering in UV agrees with an optical thickness of the scattering gas of 0.07 over the level where the optical scattering thickness by the cloud layer is equal to 1 (at λ = 3400 A), corresponding to a pressure of $\leq$55 mb.

Detailed calculations of the value of polarization according to the Mie theory (considering the contribution of Rayleigh polarization) forces us to exclude drops of water of any size as the primary form of scattering agent.

The best agreement is produced by spherical particles with low absorption, real portion of index of refraction 1.43-155 and mean diameter 2.5 $\pm$ 0.5 μ. The polarization observed for all phases is less than the theoretical, which can be explained by the dilution of once-scattered polarized light upon repeated scattering. With a pressure of 55 mb and temperature T = 235 K, many liquids cannot condense, while others deviate in their spectroscopic data. Drops of H_2O, CO_2, NH_3, SO_2, etc. did not fall within these limits of refractive index. Although the theory of Mie is not applicable to aspherical particles, the results produced can be applied to solid particles of SiO_2 and NaCl.

V. V. Sobolev studied the dependence of polarization of the light of Venus on phase angle [34]. /35

The degree of polarization was calculated for two models of the atmosphere: 1) molecules and larger particles mixed in a constant ratio; 2) over the cloud layer of Venus is a layer of low optical thickness with n = 1.50. The theoretical results agree with the observational data with a mean particle diameter of 2 μ. In order to explain polarization in the UV-area, it is sufficient to assume that the share of molecular scattering in UV-rays amounts to 12% (model 1) or τ_0 = 0.03 (model 2).

In conclusion, we should note the calculations of Skotnikov [33] of the refraction of light in the atmosphere of Venus, based on data from measurement of parameters of the atmosphere by the Venera 4 spacecraft. According to these calculations, at a slight altitude over the surface of the planet the horizontal rays travel around the planet in a circle. Rays departing at angles to the horizon of not over 2° return to the surface.

Radar Characteristics of the Surface. The first reliable data on the surface of Venus were produced by studies of the characteristics of radar reflections, as well as by measurements of differential polarization of the natural radiation of the planet by Kuz'min and Klark [20].

Radar studies of Venus have now been performed over a broad range of wave lengths.

The results of many determinations of the radar reflective capacity of Venus indicate that for $\lambda > 20$ cm it is practically constant and amounts to about 15%; this is approximately double the albedo of the moon.

For example, observations of a reflected signal from Venus at a frequency of 38 MHz led James, Ingalls and Rainville [110] to estimate the effective radar cross section of Venus as ~13%; strong signal fluctuations were observed. Boyer and Newell [61] attempted to find a correlation between the spots on the disc of Venus observed in UV-rays and the effective reflective cross section at λ = 3.8 cm, but were unsuccessful.

Aleksandrov, Kuznetsov and Rzhiga [3] determined the back scattering diagram of Venus at λ = 40 cm from the Doppler spectrum and the distribution of the energy of reflected signals by range. Both methods yielded identical results and agreed well with the theoretical dependences on the assumption that the primary portion of the energy was reflected specularly, while a certain portion was scattered diffusely by surface elements with dimensions comparable to the wave length. The smoothness factor of the diffuse surface was 0 and 1.

Evans and Ingalls [88] studied the radar reflective capacity of Venus at various wave lengths. Analyzing the results of radar studies of Venus by the Lincoln Laboratory in 1964, 1966 and 1967, they determined that the effective reflecting cross section was 1.7% for λ = 3.8 cm; 11.5% for λ = 12.5 cm and $\geq$15% for λ = 23 cm. In their opinion, the higher value of effective cross section than that observed for the moon can be explained by the greater density of the surface of Venus. The drop in cross section at shorter wave lengths by approximately an order of magnitude can be explained by absorption of radio waves in the atmosphere of the planet. /36

To study the absorption of radio waves in the atmosphere of Venus, Ho and Kaufman [116] performed laboratory measurements of the absorption factor of microwaves in CO_2, Ar, N_2, H_2O and Ne. A reflective spectroscope with a resonator was used in the measurements. At $\nu > 1200$ MHz, they assumed $\alpha \approx \nu^2$; therefore, α was measured at a single frequency ν = 9260 MHz. The pressure was varied up to 130 atm, T -- within limits of 240-500 K.

Subsequently, Muhleman [137] used the results of radar observations of Venus to determine the optical thickness of the atmosphere in the 3.6 cm-7 m range as a function of wave length and di-

electric constant. He found the following rule for optical thickness:

$$\tau(\lambda) = (1.01 \pm 0.04)(3.8/\lambda)^2,$$

where λ is the wave length in cm. The dielectric constant is equal to 4.8 ± 0.3. Radio interferometric observations at 10.6 and 3.1 cm agree with the radar data. The observed nontransparency can be explained by CO_2 absorption with a pressure at the surface of ~100 atm.

Viktorova and Naumov [9] studied the influence of dimers and monomers of water vapor H_2O on the absorption of radio waves in the centimeter, millimeter and submillimeter bands. According to their calculations of the absorption factor of the dimer of water vapor $(H_2O)_2$, its absorption in the atmospheres of Mars and Venus, in contrast to that of Earth, can be completely ignored.

The Search for Other Radiation from Venus. Haymes, Ellis and Fishman [100] attempted to detect X-ray radiation from Venus.

The observations were made from a high-altitude balloon at a residual atmospheric pressure of 2.8-3.4 g/cm^2. Within the limits of accuracy of the measurements, no photons with energies of 40-100 kev were observed. This indicates an upper limit of the intensity of X-ray radiation from Venus in this range of $1.8 \cdot 10^{-2}$ photons/cm^2·sec.

After processing 129 visual observations of the glow of Venus made in 1954-1962, Levin [123] noted a general increase in [illegible -- tr.] on the days when the glow was visible in the inferior conjunctions. Levin relates this phenomenon to the glow of the atmosphere of Venus similar to terrestrial polar auroras, caused by bombardment with solar particles. /37

Goody and McCord [95], using the 200-inch Palomar reflector, searched for atmospheric glow emissions in the 4000-8000 A wave length range in intervals 200 A wide. The results were negative.

9. Radio Temperatures and Thermal and Dielectric Properties of the Surface of Venus

Radioastronomical observations have shown that the brightness temperatures of Venus in the centimeter and decimeter wave bands are on the order of 600 K, falling to 350 K in the millimeter wave band (at λ = 20 μ, according to the observations of Lowe, T = 248 K [127]). The generally accepted explanation of this difference is that the 600 K temperature relates to the surface of the planet, the 350 K temperature -- to a certain level in the atmosphere which absorbs and reradiates the millimeter radiation of the

surface. Observations of Venus near λ = 1 cm are of great importance for determination of the agent which absorbs the millimeter radiation.

Observations. Griffis, Thornton and Welch [98] studied the radio radiation of Venus in the 18-26 and 26-40 GHz range using the 3-meter radiotelescope of the University of California. Their results are as follows:

Frequency, GHz	18.5	20.60	22.235	24,14	26.0	30.9	36.06
T, K	560±51	595±50	500±70	451±53	495±50	412±55	390±45

The measurements were compared with the spectra of 8 theoretical models consisting of CO_2, N_2, water vapor, as well as clouds of water, ice and dust particles in various proportions. None of the models corresponded to the observed spectrum of Venus.

Law and Stealin measured the brightness temperature of Venus near λ = 1 cm in January and March of 1966 and produced the following figures [122, 174] (error of determination ±10%):

λ,cm	1.18	1.28	1.35	1.43	1.58
T, K	400	418	456	451	477

Finally, Kalaghan and Wulfsberg [114], observing the bright planets using a 9-meter telescope at λ = 8.6 mm, produced for the brightness temperature of Venus $T_b = 423^{+42}_{-30}$ K. Staelin and Reifenstein [175], observing Venus and Jupiter with the MIT 8-meter radiotelescope in the 19.0-25.5 GHz range, found no variations in the radio radiation of Venus. However, Epstein et al [87], measuring the brightness temperature of Venus, found that at 3.4 mm the brightness temperature of Venus varied with phase angle i according to the rule /38

$$T_b = 296 - 11[\cos(i - 1)] \text{ K.}$$

This dependence is opposite that observed at longer wave lengths.

The dependence of the brightness temperature of Venus in the millimeter wave band on phase angle was confirmed by Kalaghan and Wulfsberg by their observatiosn using the 9-meter radiotelescope at the Air Force Cambridge Research Laboratory at λ = 8.6 mm [115].

A modulation radiometer was used with a sensitivity of 0.3 K at τ = 1 sec. The Jupiter test indicated T_b = 142 ± 6 K. The method of least squares was used to produce the phase curve

$$T_b = (425 \pm 2) + (10 \pm 4)(\cos i - 13 \pm 11)\ K,$$

where i is the phase angle (in the inferior conjunction i = 180°). Fluctuations were observed; furthermore, a systematic error of ±7% is possible.

Morrison [134], observing Venus in 1967-1968 using the 43-meter Greenbank radiotelescope and a frequency of 15.4 GHz, produced, by comparison with Devoi-A, $T_b = 485^{+60}_{-40}$ K. The phase effect at λ = 2 cm is practically absent: the upper limit of the change in T_b with phase is not over 5%.

Observations of Venus were also continued in the centimeter wave band. Dickel [78], using the 42-meter radiotelescopte of the National Radio Observatory at Greenbank in February of 1966, produced at λ = cm T_b = 700 ± 45 K (callibration performed using radiosource Hydra-A). Dickel and Medd [80] produced T_b = 653 ± 40 K at a wave length of 4.5 cm.

Analyzing the results of his observations of 1966, Dickel [79] concluded that the observed increase in brightness temperature with increasing wave length can be explained by the increasing contribution from deeper layers of the atmosphere and the surface of the planet. The radiation becomes Planck radiation at λ = 6 cm. Estimates of the polarization of the radiation yields 0.5 ± 0.9%, indicating a low temperature gradiant from the equator to the poles.

The absence of any significant brightness temperature gradiant of Venus from the equator to the poles has been confirmed by Gale and Sinkler [90], who indicated that results published in 1965 by Kuz'min and Klark at λ = 10.6 cm, indicating that the temperature at the poles of Venus is 25% lower than at the equator, were erroneous. Reanalysis of the [blank -- tr]ometric data which led to this conclusion indicated that there were systematic errors. New measurements at λ = 3.12 cm showed that the reduction in temperature is not over 3%. /39

It should be noted that neither Venera 4 nor Mariner 5 confirmed the presence of a phase effect in the microwave band (including the higher temperature in the day than at night), or the relatively low temperatures near the poles. Both would be very important for the dynamics of the atmosphere [105].

Interpretation of Thermal Radio Radiation. Pavel'yev and Strelkov [29] theoretically calculated distribution of radio brightness temperature over the disc of Venus at wave lengths of 1.9 and 1.35 cm for a spherically symmetrical model of the atmos-

phere of Venus with the greenhouse effect. The calculations agreed well with the results of the measurements of Mariner 2 [147].

In [44] Troitskiy presented a review of the theoretical and experimental work on the thermal radio radiation of the moon and Venus. He presented solutions to the heat conductivity equations for the cases of periodic (insolation) and aperiodic (eclipsing) heating modes. He produced general expressions for the distribution of radio brightness temperature over the disc of the planet and a formula expressing the integral radio radiation through the radiation of the disc of the planet. If we assume that the surface layer is homogeneous and smooth and is a dielectric, we can produce three parameters:

$$\varepsilon=\varepsilon(\varepsilon_0, \rho);\ \gamma=(k\rho c)^{-1/2};\ c\gamma/b\sqrt{\varepsilon},$$

which relate the six unknown quantities ε_0, ρ_0, k, ρ, c and b = tan Δ/ρ. For silicates, $\varepsilon = \varepsilon(\rho)$, c = 0.2; the values of k, ρ and b are defined unambiguously. If the density varies with depth, radar measurements can be of assistance. According to the data of the phase dependence of the radio radiation of Venus at λ = 3.2 and 10 cm, we produce a value of $m(\delta - m\lambda) = 0.14$; $\gamma \approx 150$.

Noting the significant differences in estimates of the value of dielectric constant of the surface of Venus of various authors, Strelkov [40, 41] suggested a two-layer model of the upper cover of Venus, which can also explain the differences in the values of brightness temperature of Venus in the centimeter and decimeter wave bands.

Determination of the parameters of the surface of Venus can also be based on the results of radar observations of Venus.

The nature of the reflected signal, namely the fact that the diameter of the zone effectively reflecting radiation is approximately 1/3 the radius of the planet, while depolarization of the reflected radiation is also slight (not over 10-15%), indicates the specular nature of reflection from the surface of Venus [40, 41]. It is this type of reflection which would be expected from a wavy dielectric surface, the dimensions of irregularities and radius of curvature of which are much greater than the wave length. /40

The dielectric permeability of the surface of Venus, determined from the energy of specular reflection in the decimeter band, falls between 3.5 and 6. Approximately the same value is characteristic for dry rock based on silicates [8].

Aleksandrov and Rzhiga [4] indicated the need to consider diffuse scattering in determining the coefficient of reflection of

the planets from radar data. In particular, their calculations showed that for Venus, based on radar studies at λ = 40 cm, the value of the dielectric constant $\varepsilon = 4.5(+1.4; -1.0)$; ignoring diffuse reflection, the value of ε produced is 20-25% greater.

Measurements of differential polarization of the natural radiation of Venus at λ = 10.6 cm [20] indicated a value $\varepsilon = 2.2 \pm 0.2$. However, after introduction of corrections for absorption of radio waves in the atmosphere of Venus and the roughness of the surface, this determination agreed with the radar data.

10. Composition of the Atmosphere

Any complete study of the atmosphere of the planet must include studies of its lower atmosphere, including the weather processes occurring under conditions of thermodynamic equilibrium; the upper atmosphere, including aeronomic processes, related to ionization under the influence of sunlight and photochemical processes between components of the atmosphere; the study of the plasma near the planet.

There is no doubt that the interplanetary plasma has a slight influence on the ionosphere of the planet; the ionosphere has no significant influence on the lower atmosphere. On the other hand, the lower atmosphere is the source of components of the upper atmosphere and to a significant extent determines its temperature; it supplies the outer layers with dynamic energy and thermal radiation.

Thus, we cannot understand the processes occurring in the atmosphere until we know the physics, chemistry and dynamics of its main mass.

The atmosphere of Venus above the cloud layer is accessible to studies by optical means; the same means allow us to study the upper layers of the clouds. However, the rest of the cloud layer and particularly the area of the atmosphere below the cloud layer can be studied only by direct methods. Observations of the natural radio radiation of the planet and the transmission conditions of radar signals can produce only very indirect data on the lower atmosphere of Venus. /41

It is these considerations which have determined the decisive significance of direct measurements of the composition and physical conditions of the lower atmosphere of Venus by means of the Venera descent modules. Establishment of the fact that the atmosphere of Venus consists primarily of carbon dioxide and that the pressure at the surface is on the order of 100 atm, while the temperature is $\sim$500° C, provided a firm foundation for interpretation

of all of the rich material accumulated from observations and opened a path for advancement toward better understanding of the conditions on the planet closest to the Earth, long considered a "sister" of the Earth.

Spectroscopic Observations and Composition of the Atmosphere Over the Cloud Layer

In 1932, Adams and Dunheim, using the 100-inch reflector of Mount Wilson, detected four strong absorption bands on spectrograms with high dispersion in the red and infrared areas of the spectrum. They found no bands for O_2 or H_2O vapors. The bands detected were identified with CO_2, which was confirmed by laboratory measurements with a 20-meter tube filled with CO_2.

The spectroscopic studies of the absorption bands of Venus were performed both in order to determine the period of rotation of Venus, and in order to find the H_2O and O_2 bands of Venus. However, the successes in this area were long quite modest, and only the development of methods of Fourier spectroscopy allowed high precision terrestrial spectroscopy of Venus to be conducted.

Essentially, the Fourier spectrum (interferogram) of a planet contains in coded form all information necessary for reconstruction of the spectrum. This information can be produced by analyzing the frequencies by [illegible] processing of the spectrum using large computers.

It is the application of Fourier spectroscopy methods which has made it possible to produce the spectra of the primary components of the atmosphere of Venus, CO_2 at very high pressure, while the structure of the CO_2 bands has been used to estimate the temperature [illegible] for the level of the atmosphere where the bands arise, and detect HCl, HF and CO and certain other small components in the atmosphere of Venus.

Carbon Dioxide

High-resolution spectra of Venus have been found to contain thousands of lines of CO_2 and its isotopic modifications. Studies of the CO_2 lines in the 1-25 μ area has shown [178] that their half width is <0.03 cm^{-1}; therefore, the total CO_2 pressure in the absorbing layer is not over 0.3 atm. /42

Using the example of processing of measured contours of the CO_2 band at 7820 A, Grey [96] compared four methods of determination of the rotary temperature:

1. The ordinary method used by Spinrad.
2. The same method but using weights proportional to the inverse square of the deviation from the mean value $y = \ln(W/J)$, where W is the equivalent line width.
3. A method based on determination of the angular coefficient of the growth curve with a certain fixed value of temperature.
4. The method of successive approximations, finding simultaneously b and T.

In the first two methods, it was assumed that b = 1.0 or 0.5 (depending on whether the bands correspond to the linear or quadratic section of the growth curve), while the temperature is found by solution of a system of arbitrary equations; in the third method, a value of b is used produced from the solution where $T = T_0$ (= 240 and 300 K), while the order of the operations is the same.

In seven of ten cases, b ≈ 0.5, in two -- near 1.0; one case is intermediate, b = 0.75. The temperatures calculated by the fourth method have less spread and lower mean error: 216-419 K, averaging 285 K; no dependence on phase angle is observed. The equivalent widths decrease with increasing phase. The quantity of CO_2 absorbing is 2.2-4.5 km·atm; the pressure at the level of formation of the lines is 200-40 mb.

Schorn, Gray and Barker [163] studied the band at λ = 7820 A in the spectrum of Venus from April through December of 1967. The spectra were produced at the focal point of the Struve reflector by means of a camera with a focal length of 160 cm. The dispersion was 2 and 4 A/mm. The method of least squares was applied to the results of observation to determine the rotation temperatures. Either a linear absorption rule or an exponential rule with exponent 1/2 was used. In the former case, the temperatures determined lay within limits of 207-264 K. In the latter case, when the slope of the growth curve was determined, the corresponding temperatures were 225-262 K. In both cases, the rotational operators, in agreement with the results of Gray [96], showed no significant variation with phase angle within $50<i<90°$. The mean value, according to both methods, was 242 ± 2 K (formal error). The spatial and time variations of the apparent quantity of CO_2 along the path over which absorption occurs was also studied; significant changes with time were noted. The total quantity of CO_2 along the total absorption path, added to 3.1 ± 0.3 km·atm, which agrees with similar results produced on the 1.6 and 2.8 μ bands at similar phase angles. /43

Based on the results of studies of the 7883 A band, Schorn, Gray and Barker [97] produced 12 spectrograms on the same instrument, indicating a rotational temperature of 244 ± 10 K. The mean

rotational temperature on the basis of both lines at 7820 and 7883 A was 245 ± 6 K.

Oxygen

Prokof'yev and Petrova [31], studying high-resolution spectra of Venus at 6300, 6900 and 7600 A with great Doppler shift of the lines in the spectrum of Venus found weak O_2 lines.

The searches of Belton and his colleagues near the middle of the A band of O_2 showed no spectral peculiarities which could be attributed to oxygen in the atmosphere of Venus. Therefore, the upper limit of the oxygen content of the atmosphere of Venus $O_2/CO_2 \approx 4 \cdot 10^{-5}$ [178].

Beckman [55], using a solar spectrograph and an image intensifier, attempted to find O_2 in the atmosphere of Venus. He succeeded in finding the Doppler companions of the lines at 6306.6, 6305.8 and 6302.8 A. The upper limit of the content of O_2 is 1.75 m·atm.

Water Vapor

One great achievement of spectroscopy was the detection of water vapor in the atmosphere of Venus by means of observations from balloon [82]. Improvement of the methodology allowed water vapor to be observed in the atmosphere with terrestrial observations as well.

For example, Spinrad and Shawl [176], using three spectrograms of Venus with dispersion 1.9 A/mm, produced at the focal point of the 3-m lick reflector, found the companions of the telluric H_2O line at 8190 A. The total quantity of water vapor in the beam of vision is ∿250 μ precipitated water; if we assume the mean air mass to be 4, the quantity of water over the cloud layer is equal to ∿60 μ, which agrees with the results of the balloon observations.

In 1965-1966, Belton and Hunten [56] produced spectra of Venus with a resolution of 0.1 A in the area of the H_2O band at 8190 A by means of a multichannel photoelectric system with accumulation. The observations were performed with the 12-meter spectrograph of the Halberg McMath solar telescope. The equivalent width of the red companion of the 8189 A line is about 20 mA. The profile of details indicates an equivalent pressure of about 5 atm. The total quantity of water on the ray of vision was 317 μ, or ∿125 μ over the cloud layer, which also does not contradict the results of the balloon measurements. These determinations /44

were put in doubt by Owen [141], who reported that the spectrograms of Venus show only one Doppler companion in the H_2O band at λ = 8200 A. In his opinion, this might be a Fraunhofer line. In this case, the upper limit of precipitated water in the atmosphere of Venus would not be over 16 μ.

Answering Owen, Hunten, Belton and Spinrad [104] indicated that the contribution of Doppler lines is slight, and the objection of Owen is invalid.

Continuing the study of the spectra of Venus with high dispersion, Schorn et al [162] produced 22 spectra of Venus with the 82-inch reflector of McDonald Observatory with dispersions of 2 and 4 A/mm in April-June of 1967. The authors detected no Doppler companions with the H_2O line at 8200 A, indicating that the upper limit of precipitated water is 32 and 16 μ for dispersions of 2 and 4 A/mm respectively.

In November-December of 1967, Schorn et al found Doppler companions; the quantity of precipitated water was 30-40 μ. According to other observed Doppler companions, estimates have been given from 4-292 μ precipitated water; it is possible that the content of water vapor in the atmosphere of the planet actually fluctuates.

On 27 and 28 November 1967, Kuiper produced spectra of the moon and of Venus with a resolution of 8 cm^{-1} from a high-altitude jet aircraft [120].

In order to exclude the remaining slight telluric absorption, as well as solar absorption lines, a relative Venus/moon spectrum was constructed, allowing direct comparison with laboratory spectra. On 5-6 May 1968, a more precise spectrum of the moon was produced, which was also used to construct a relative spectrum of Venus. Finally, in order to increase the accuracy of the relative spectrum of Venus outside the area of the telluric H_2O bands, terrestrial spectra of Venus and the moon and their relationship were used.

The study of the Doppler shift of the planet (v = 12.9 km/sec) shows that in the area of the bands of water at 1.4 and 1.9 μ, the telluric and Venusian lines are fully separated. However, the lines of the H_2O band near 2.6 μ, which are rather strong in the telluric spectrum and are doubled even at a pressure of 200 mb, are generally not separated in the Venusian spectrum. Under these conditions, determination by means of the 2.6 μ band in the relative spectrum gives an artificially low content of water in the atmosphere of Venus. Callibration of the 1.4 and 1.9 μ bands by means of a 6-m tube containing laboratory air under a pressure

of 200 mb shows that the quantity of water in the spectrum of Venus corresponds to 5 μ precipitated water; the H_2O/CO_2 ratio is $1 \cdot 10^{-6}$.

According to a work of Connes et al [70], the quantity of H_2O /45 is not over 20 μ precipitated water. Comparing the quantity of water in the atmosphere of Venus and the hydrosphere of the Earth, Rasool [151] showed that Venus is 10^4 times poorer in water. Even a small quantity of water, naturally, requires the existence of a mechanism for its loss. In the opinion of Rasool, water is separated from the depths of the planet, evaporates, rises upward and is dissociated by UV-radiation; the hydrogen then dissociates, ionizes and dissipates, while the oxygen oxidizes CH_4 and CO to CO_2. The rate of dissipation of hydrogen is estimated as 10^{11} molecules/$cm^2 \cdot$sec with a temperature of the exosphere of ~650 K.

Minor Components of the Atmosphere

HCl, HF and CO. In July of 1966 at the St. Michel Observatory, P. Connes et al [70], using a Fourier spectrometer, produced a spectrum of Venus in the 1-2.5 μ area with a resolution of ~0.08 cm^{-1}. After averaging the recordings for various days by computer, a spectrum was produced separately for large and small air masses and the spectrum of the sun with the same resolution. The accuracy of measurements was $1 \cdot 10^{-3} cm^{-1}$.

In the 1.72-1.79 μ area, an oscillating-rotating HCl spectrum was produced [first harmonic, transition (2.0)]. The telluric H_2O and CH_4 lines and the Venusian CO_2 band fall easily on the R-branch. Two series of narrow lines with a ratio of intensities of 3:1 can be related to HCl^{35} and HCl^{37}. The R-branch falls in a less favorable area of the spectrum for observations.

Determination of the absolute concentrations of spectroscopically observed gases is difficult due to the inaccuracy of the estimates of pressure, cloud altitude, number of reflections and scatterings in the cloud layer, etc.

It is therefore necessary to make do with relative contents. If HCl is evenly mixed with CO_2, $HCl/CO_2 \approx 0.6 \cdot 10^{-6}$ (±20%).

The second small component discovered from the oscillating-rotating spectrum is HF. Its lines are strongly blended by the telluric CH_4 and H_2O bands, but the line at 2.47 μ is not blended and its length corresponds marvelously with the laboratory value. With homogeneous mixing with CO_2, the HF/CO_2 ratio $\approx 5 \cdot 10^{-9}$ (±2 times).

The third gas identified with confidence is CO; the line at 2.35 μ, corresponding to transition (2,0) has been reliably identified. Up to 1966, the existence of CO in the atmosphere of Venus was under doubt. Sinton (1963) and Moroz (1964) found indications of the presence of CO, while Kuiper (1962) found no trace of CO [26]. Improving the resolution of spectra by two orders of magnitude, J. and P. Connes reliably identified 39 CO lines and estimated its content [178]. The data produced indicate the presence of $C^{13}O^{16}$ and $C^{12}O^{18}$; $C^{12}O^{17}$ was not found. The intensities /46
of the CO lines indicate that CO is present not only in the photochemical area of the atmosphere of Venus (where CO_2 is dissociated by solar radiation), but is more probably mixed throughout the entire mass of the atmosphere. The ratio $CO/CO_2 \approx 46 \cdot 10^{-6}$. The mean temperature of CO is 240 K, the mean pressure 60 mb. This value of temperature agrees with CO_2 but is slightly lower than that of HCl (270 K and 80 mb).

No other gases with hydrogen in their composition have been found [144]. The upper limits of the content of CH_4, CH_3CL, CH_3F, C_2H_2 and HCN in relationship to CO_2 are on the order of 10^{-6}.

Swings [178] presents the following summary of determinations of the minor components in the atmosphere of Venus (see Table 2).

TABLE 2. CONTENT OF MINOR COMPONENTS IN THE ATMOSPHERE OF VENUS

Component	Pressure, bar	Author and year
CO	$9 \cdot 10^{-6}$	Kaplan, 1967
H_2O	$1{,}1 \cdot 10^{-5}$	Strong et al, 1965
»	$1{,}3 \cdot 10^{-5}$	Belton and Hunten, 1966
»	$6 \cdot 10^{-6}$	Spinrad and Shawl, 1966
»	$10^{-6} - 10^{-7}$	Kuiper, 1967
HCl	$6 \cdot 10^{-8}$	J. and P. Connes, 1967
HF	$5 \cdot 10^{-10}$	J. and P. Connes, 1967

Mueller [135] explained the presence of HCl and HF in the atmosphere by the decomposition of halogen-containing materials under the high-temperature conditions at the surface of the planet.

O_3. Fabian and Libby [89] calculated the possible vertical distribution of ozone in the atmosphere of Venus between the upper boundary of the cloud layer and the 90 km level (from the level of transmission of the last signal of Venera 4) for three values of oxygen content in the atmosphere of Venus (0.5, 1.0 and 1.5%).

The height of the clouds is 30 km. According to these calculations, ozone has a maximum at an altitude of 35 km; the values of its content at the maximum are $8 \cdot 10^{-3}$ and $4 \cdot 10^{-3}$ for the equator and latitude 60° respectively. The total content of ozone above the level of the clouds (36 km) is 0.008 and 0.044 cm O_3 (at standard temperature and pressure) for the day hemisphere of Venus.

C_2O_3, COS, H_2S, etc. Kruickshank and Kuiper performed a systematic study of the spectra of carbon suboxide C_2O_3 under laboratory conditions with the purpose of subsequent search for traces of C_2O_3 in the atmosphere of Venus. The search for C_2O_3 bands in the 3100-3600 A wave length range was not successful: no bands were detected [73]. Then Kuiper et al studied the infrared spectra of C_2O_3 in the 1-2.5 μ [121] and 2-15 μ [74] areas. The most suitable band, in their opinion, is the band near 6.37 μ, search for which in the spectrum of Venus must be performed from high altitudes, in order to avoid blending with telluric H_2O bands. /47

Kuiper and Kruickshank also studied the presence of various compounds containing sulfur in the atmosphere of Venus. The 1.5-m reflector of the Catalina Observatory (altitude 2520 m above sea level) was used, producing a spectrum of Venus in the 3000-3200 A range with a resolution of 8.1 A/mm, and it was compared with laboratory spectra of SO_2 [71]. No SO_2 bands were found in the spectrum of Venus, indicating an upper limit of the SO_2/CO_2 ratio of $5 \cdot 10^{-8}$. Kruickshank [72] compared the spectra of Venus and the laboratory spectra of COS and H_2S in the 0.9-2.6 μ range.

Since the bands sought were not found, the following estimates were produced for the content of these small components:

$$COS/CO_2 \approx 10^{-6},$$
$$H^2S/CO_2 \approx 2 \cdot 10^{-4}.$$

Rocket Studies of UV-Spectra and Small Components

Yet another powerful method of investigation of the atmosphere of Venus consists in studies of the spectra of the planet in the far ultraviolet range by means of instruments carried on rockets. Moose, Fastie and Bottemy published the results of rocket studies of Jupiter and Venus [132]. Using an Aerobee rocket, a 35-cm telescope with a relative aperture of 1:2.2 and an LiF prism objective was lifted to a height of 157 km. The receiver used was a photomultiplier. The lines at 1216 and 1304 A (18 and 11 kR respectively) were detected in the spectrum of Venus; the albedo increases in the direction of longer waves, although only sightly.

Successful rocket studies were performed by Evans and Jenkins et al [178].

Evans used diffraction spectrographs launched on rockets and found a sharp drop in the albedo at 3000 A and a minimum of reflective capactiy at 2500 A. These observations can be explained by Rayleigh scattering, superimposed on the reflection from the cloud layer.

Jenkins et al used a diffraction spectrograph to produce rocket spectra in the area from 2100-3070 A, with a resolution of ~1 A. Weak, unidentified bands were observed between 2174-2450 A. The drop in albedo near 2200 A might be caused by the presence of traces of COS. The following upper limits were determined for the contents, due to the absence of any measurable absorption: /48

O_3	$5 \cdot 10^{-4}$	cm·atm
NH_3	$9 \cdot 10^{-3}$	"
SO_2	10^{-3}	"
NO_2	$6 \cdot 10^{-2}$	"
NO	10^{-1}	"
C_2O_3	$5 \cdot 10^{-1}$	"

Hydrogen and Deuterium in the Upper Atmosphere of Venus. Special photometers were carried on board the Venera 4, 5 and 6 spacecraft, as well as Mariner 5, to detect Lα and the OI 1304 A line. The photometers on board the Soviet spacecraft performed measurements in two regions of the spectrum at 1050-1340 and 1225-1340 A. The night side of Venus was studied. The measurements detected the Lα radiation; the intensity of the OI triplet was either extremely low or it was totally absent. Based on the observations of Venera 4, the concentration of atomic hydrogen at a distance of 10,000 km from the center of the planet on the night side was 50 cm^{-3} [21].

Mariner 5 carried three UV-photometers for observation of Lα and OI emission. On the long wave end, the radiation cut off at 2200 A; on the short wave end -- at 1050, 1250 and 1350 A respectively. The observations indicated a sharp deficit of atomic oxygen and allowed the hydrogen corona of Venus to be discovered.

Upon approach to Venus, the photometers recorded the galactic background (the signal for Lα corresponded to 0.59 kR). Then, as the spacecraft flew by close to Venus, the photometers gradually observed the outer atmosphere on the night side (a weak night glow of unknown origin was observed in the UV), the dark planet, the area of the terminator and, finally, the day side; then the bright limb, outer atmosphere and finally the galactic background once more came within the field of vision of the instruments [54].

Analyzing the measurements of Mariner 5, Wallace [81] concluded that the Lα radiation arises as a result of the scattering of sunlight on atoms of H and (or) D. The existence of a purely hydrogen exosphere is impossible. According to his estimates, the exosphere contains a mixture of H and D, its temperature at the subsolar point is ∿650 K. At a distance of 650 km from the center of the planet, the content of H atoms is $6 \cdot 10^3$ cm^{-3}, that of D -- 10^5 cm^{-3}. At the antisolar point, the quantity of deuterium decreases by a factor of 10, of hydrogen by a factor of 2.

McElroy and Hunten [129] discussed various possible explanations of the Lα line observed by Mariner 5 and concluded that these lines cannot be explained by assuming the presence of atomic hydrogen alone. The observations are satisfied by a 2-component atmosphere, but the second component cannot be H_2 or H at another temperature. The observations are best satisfied by the presence of deuterium with D/H ≈ 10 at the base of the exosphere. Transfer through the thermosphere increases the D/H ratio by 100 times, so that in the lower layers it might be ∿0.1. Isotopic separation is being studied under the conditions of Venus with thermal dissipation, which is particularly easy there, since the reserves of H are not supplemented by the oceans. The necessary initial value of H_2O is <0.1% that of the Earth; the remaining vapor dissipated in early stages. /49

Composition of the Lower Atmosphere of Venus According to the Direct Measurements of the Venera Spacecraft

Results of Studies of the Venera 4 Spacecraft [1, 10]

Statement of the Experiment. On 12 June 1967, the Soviet Venera 4 spacecraft was launched. Following 128 days of flight, the spacecraft entered the atmosphere of Venus and made a soft landing on the night side. The spacecraft consisted of two main parts -- the orbital section and the descent module; the descent module weighed 383 kg and was similar in shape to a sphere ∿1 m in diameter. It carried instruments for determination of the temperature, pressure and chemical composition of the atmosphere of the planet. All measurements were performed in the atmosphere of the planet during the parachute descent of the spacecraft.

The chemical composition of the atmosphere was determined by special gas analyzers. The descent vehicle carried 11 analyzers, combined into two groups of 5 and 6 analyzers respectively. The analyzers were put in operation on instructions from the time programming device. The first group of analyzers went into operation at p ≈ 550 mm, the second -- at ∿1500 mm; T = 25 ± 10 and 90 ± 10° C respectively.

Apparatus and Methods of Determiantion of the Composition of the Atmospehre. The composition of the atmosphere was determined using reactions which have been well studied and are sufficiently selective. In order to increase the reliability of measurements, both threshold and amplitude sensors were used. Each gas analyzer was a cylinder of a given volume, separated by a membrane into two sections. One section contained a chemical absorbent, which absorbed the component to be determined. Until the moment of measurement, both sections were evacuated and sealed. During the analysis, the atmosphere of the planet entered both sections simultaneously, after which they were once more sealed and the difference in pressure resulting from the absorption of the component being defined by the absorbent in one of the sections was recorded. More sensitive physical-chemical methods were used to determine the minor components of the atmosphere: measurement in the difference in resistance of specially selected chemical absorbents in the different sections; the difference in heat liberation of special current-conducting elements, etc. Using these sensors, the content of CO_2, N_2, O_2 and H_2O in the atmosphere of Venus was measured; the results are presented in Table 3. /50

The data from the table and estimates of the accuracy of the determinations indicate that the content of CO_2 is not less than 90%, the content is not over 7%.

The content of O_2 was determined by two sensors operating on different principles. In one, a tungsten filament was instantaneously burned (at T = 800° C) designed for a threshold of $\sim$3 mm partial O_2 pressure in the volume of the sensor, corresponding to 0.5% O_2 at a pressure of 550 mm. In the other sensor, O_2 was absorbed by phosphorous vapors (the phosphorous pentoxide formed could absorb water vapor as well). A sensor, designed for a threshold value of absorbed H_2O plus O_2 of 1.6%, indicated a negative result. Data from the joint determination of O_2 indicated that its content is not over 1-1.5%.

Water was determined by three sensors. At the upper point (H $\simeq$ 26 km), a sensor with P_2O_5, determining the sum of condensed H_2O and its vapors, indicated a content H_2O>0.65 mg/1, corresponding to a quantity of >0.1% or a dew point of -22° C. At the lower point (H $\simeq$ 20 km), the content of water vapor according to a P_2O_5 sensor was also found to be >0.65 mg/1 (>0.05%), while a pressure sensor using $CaCl_2$ as an absorbent indicated <1 mg/1 (<0.7%), corresponding to a dew point of <15°. Since the temperature of the instrument itself was no less than 25°, the losses of pressure due to condensation of steam in the instrument must be considered insignificant, and we must consider that the true upper limit of the H_2O vapor pressure was determined. Thus, the possible range of vapor pressure in the various layers of the atmosphere of Venus is

TABLE 3.

Conditions of Analysis	Component Defined	Type of Sensor	Principle of Determination	Limit of Threshold	Results
			First Group		
$H \approx 26 \pm 1$ km $p \approx 500$ mm $T = 25 \pm 10°C$	CO_2	Threshold	Heat conductivity	Threshold 1%	>1%
	CO_2	Amplitude	KOH Absorption	7—100%	90±10%
	N_2	»	After absorption of CO_2 and O_2, absorption of Zr at 1000°C	7—100%	<7%
	O_2	Threshold	Burning of W filament at 800°C	Threshold 0.4%	>0,4%
	H_2O	»	Absorption of P_2O_5, measurement of conductivity	Threshold 0.1%	>0,1%
			Second Group		
$H \approx 19 \pm 1$ km $p \approx 1500$ mm $T = 30 \pm 10°C$	CO_2	Amplitude	KOH Absorption	2—30%	>30%
	CO_2	Threshold	KOH Absorption	Threshold 1%	>1%
	N_2	Amplitude	After absorption of CO_2 and O_2, absorption of Zr at 1000°C	2,5—50%	<2,5%
	$O_2(\pm H_2O)$	Threshold	Evaporation of phosphorous	Threshold 1.6%	<1,6%
	H_2O	»	Absorption of P_2O_5, measurement of conductifity	Threshold 0.05%	>0,05%
	H_2O	Amplitude	Absorption of $CaCl_2$	Threshold 0.7%	<0,7%

between 0.65 and 11 mg/l, corresponding to dew points of -22 and +15°. As a result, the existence of liquid-drop water is possible only in the cloud layer of Venus.

Summing up, the authors of [10] give the following summary table of the composition of the atmosphere according to the data of Venera 4:

CO_2	90 ± 10%
O_2	over 0.4 but <1.5%
N_2	<7%
H_2O	1.8 mg/l

This composition excludes a significant portion of other gases which had earlier been suggested as components of the atmosphere of Venus. However, the presence of Ar and other inert gases is not excluded, although their quantity together with N_2 could hardly be over 2-4%. /52

Results of Composition Studies by Venera 5 and 6 [11]

In January 1969, the Venera 5 and Venera 6 spacecraft were sent toward Venus. Both of these spacecraft reached the planet and made smooth descents into its atmosphere. The spacecraft performed measurements on the descent sector over which the pressure varied from 0.6-27 atm, the temperature from 25-320° C.

Both spacecraft carried gas analyzers similar to those used on Venera 4. Based on the data produced by this spacecraft, the new devices included several design improvements, with narrower ranges and higher accuracy. Each spacecraft carried two devices to determine the content of carbon dioxide, nitrogen, water and oxygen in the Venusian atmosphere during the parachute descent. The measurements were conducted at pressures of ∿0.6-∿10 atm. The gas analyzers had two types of sensors, one of which performed quantitative determinations of content, while the other determined only the upper or lower limits of the content of a given component.

Each spacecraft determined the composition of the atmosphere twice. Venera 5 performed the first measurement soon after opening of the main parachute ($p \approx 0.6$ atm, $T \approx 25°$ C), the latter at $p \approx 5$ atm and $T \approx 150°$ C. Venera 6 also performed two measurements of the composition of the atmosphere at $p \approx 2$ and ∿10 atm and $T \approx 85$ and ∿225° C.

The results of the determinations by the three Venera spacecraft are presented in Table 4.

TABLE 4.

p, kg/cm²	T, °C	Result, vol.%	Venera spacecraft number
	Carbon Dioxide CO_2		
0,6	~25	97+4	V
0,7	~25	90+10	IV
2,0	85	>56	VI
5,0	150	>60	V
10,0	220	>30	VI
	Nitrogen N_2		
0,6	~25	≤3,5	V
0,7	~25	≤7	IV
2	85	≤0,5	VI
5	150	≤4	V
5	150	≤4	V
10	220	≤2,5	VI
10	220	≤2	VI
	Oxygen O_2		
0,7	~25	>0,4	IV
2,0	85	≤1,5	IV
2,0	85	≤0,3	VI
5,0	150	>0,1	V
5,0	150	≤0,1	V
10,0	220	≤0,1	VI
10,0	220	≤0,2	VI
	Water mg/l		
0,6	~25	~11	V
0,7	~25	>0,7	IV
2	85	≤8	IV
2,0	85	~6	VI
5,0	150	>0,7	VI
10	220	<0,7	VI

/53

There were two quantitative and three threshold determinations of CO_2. The authors note that the threshold determinations were significantly lower than the true content. This is explained

by the fact that the sensors were designed to operate at lower pressures, went off scale, and the table presents the upper limits of the scale. On the Venera 5 and 6 spacecraft, the pressure changed as the atmosphere was collected. Knowledge of the pressure at the level of collection of the specimen allowed the accuracy of determination of content to be increased significantly.

The content of oxygen was measured at 4 levels by 7 sensors: of nitrogen -- also at 4 levels by 7 sensors. The content of water vapor was measured at 4 levels, quantitatively at the upper points, by threshold determination in the deeper layers of the atmosphere. It follows from the table that the content of moisture decreases with depth in the atmosphere. Its quantity at $p \approx 0.6$ atm is near saturation, indicating the closeness of the cloud layer. If we extrapolate p and T into the area of lower values, we can estimate the lower boundary of the cloud layer. We find it /54 at a pressure of $\sim$0.5 atm.

Finally, the results of the experiments can be summarized as follows (see Table 5).

TABLE 5.

Component	Venera 4	Venera 5 and 6
CO_2, %	[illegible]±10	97±4
N_2, %	7 (possibly 2.5)	$\leq$2
O_2, %	0.4—1.5	$\leq$0.1
H_2O (p=0.6 atm), mg/l	1—8	$\sim$11

The data produced indicate that there are no other components in the atmosphere in any significant quantities, but do not contradict the presence of traces of CO, NH_3, HCl and the other minor components discovered spectroscopically.

The experiments of Sowerby [173] give us a clear idea of the properties of the atmosphere of Venus at the level reached by Venera 4.

The processes of oxidation and combustion were studied in an autoclave of 500 cm^3 volume under the conditions of the atmosphere of Venus. Its parameters were taken according to the data of Venera 4; pressure 20 atm, T = 270° C; composition: 98.5-99.5% CO_2, 0.4-0.8% O_2, 0.1-0.7% H_2O. Match heads, placed in this atmosphere, ignited spontaneously, but the wood did not burn, but only charred, as did cotton and fabric. Sulfur and benzene did not

burn; petroleum evaporated instantly, water boiled at 216° C. Iron, aluminum and magnesium corroded on their surfaces.

11. Physical Conditions in the Layer Beneath the Clouds

Before the launch of the Venera spacecraft, we knew very little concerning the lower atmosphere. The primary questions which needed answering were as follows:

-- Is the surface temperature actually 500-700 K as the radio measurements indicated?
-- What is the pressure at the surface?
-- What is the concentration of CO_2, the only known component of the atmosphere? Are there other gases in the atmosphere, and in what concentration?

Venera 4 showed that the main component of the atmosphere is indeed CO_2, but detected small quantities of H_2O and O_2. Mariner 5 confirmed the predominant role of CO_2. This question was studied in detail in the preceding section, dedicated to the composition of the atmosphere of Venus. Let us now go over to the results of the direct measurements of temperature and pressure in the lower layers of the atmosphere of Venus according to the data of the Venera spacecraft [1, 10, 11, 25]. /55

In order to measure the temperature, Venera 4 carried resistance thermometers with a range of measurement of 210-730 K with an error on the order of 10 K. In addition to this, the pressure was measured in the 100-5200 mm hg level with an error of ±150 mm hg, density in the range from $5 \cdot 10^{-4}$-$1.5 \cdot 10^{-2}$ g/cm^3, with an error of $(0.18\text{-}3) \cdot 10^{-3}$ g/cm^3.

Measurements were conducted right down to the point of interruption of communications with the descent module; the temperature was measured continually, the devices measuring pressure and density went off scale. The path of the descent module was determined by two methods: by the equation of motion of the apparatus with the parachute and on the basis of hydrostatic equilibrium of the atmosphere. The mean temperature gradiant in the atmosphere was found to be 9°/km, which is near adiabatic and corresponds to conditions of convective equilibrium. At the moment of interruption of communications, the pressure was 20 ± 3 atm, the density $19 \cdot 10^{-3}$ g/cm^3 ± 15%, the temperature 544 ± 10 K; the scale of altitudes was 12 km.

Thus, the first direct measurements indicated an almost linear course of temperature of the atmosphere of Venus during the descent sector measuring some 26 km in length. Over this sector, the temperature changed from 25 ± 10° C to 270 ± 10° C, the pressure from 0.7-20 atm; the course of this change was nearly adiabatic.

Venera 5 and 6 performed similar measurements over descent sectors measuring 36 and 38 km respectively and expanded the area of direct measurements in the atmosphere of Venus to temperatures of ∿600 K and pressures of ∿27 atm [6].

As the Mariner 5 spacecraft flew by Venus, the method of radio occultation was used to study the course of electron density in the ionosphere of Venus on the day and night sides in detail and to calculate the density and temperature of the atmosphere at comparatively high altitudes [118, 172]. The calculation was performed using data on the chemical composition of Venus provided by Venera 4.

It should be noted that in the Mariner 5 experiment, the level at which the measurements were performed did not relate to the surface of the planet, but rather to the center of mass of Venus. Therefore, in order to determine the distribution of temperature and pressure with altitude, one must know the distance of the surface of a given area from the center of mass.

The results of the Mariner 5 measurements agree well with the results of measurements on the Venera spacecraft in the temperature and pressure range of 300-400 K and 0.5-5 atm. Measurements /56
in other ranges where the experiments did not overlap supplement each other, so that in general we produce the distribution of temperatures in the altitude range up to ∿50 km and the change in pressure from 0.08 atm to 27 atm, temperature from 240-600 K.

The measurements of Venera 5 terminated at altitudes of 24-26 km, of Venera 6 -- at 10-12 km over the local surface of the planet. Measurements of Mariner 5 could not be performed below the level corresponding to a pressure of ∿5 atm, since, due to refraction, the deeper layers are inaccessible to measurement by radio occultation.

Due to this, data on the near-surface area of the atmosphere must yet be based on radio astronomy and radar methods plus extrapolation of the measurements of the Venera and Mariner 5 spacecraft.

The information on the surface temperature of Venus presented in Section 9 correspondingly indicates a value of 700 ± 50 K.

Extrapolation of the results of measurements by the Venera 5 and 6 spacecraft to the local surface of the planet (determined by the radio-altimeter at the point of descent of the spacecraft), on the assumption of an adiabatic atmosphere, indicates a value of 800 K and 140 atm at the point of descent of Venera 5 and 670 K and 60 atm at the point of descent of Venera 6.

Thus, we can consider it firmly established that the lower atmosphere of Venus has a very high temperature (up to ∿700 K for the mean surface), high pressure (up to ∿100 atm for the mean surface); the primary component of the atmosphere is CO_2; the temperture gradiant in the area studied (excluding the near-surface layer, where no direct data are available) is near adiabatic.

12. Mechanisms of Heating of the Surface and Models of the Atmosphere

Problems of the Greenhouse Effect

The origin of the reliably established high temperature of the surface of Venus, ∿700 K, is not easy to explain, and all models suggested encounter significant difficulties. The simplest of these is the model considering the "greenhouse effect." If we assume that the atmosphere transmits a portion of the solar radiation but is nontransparent in the IR-area, the thermal radiation leaving its surface would be "captured," and radiation out into space would occur only from the colder outer layers of the atmosphere or the cloud layer. The greenhouse effect in the Earth's atmosphere is ∿30°; in the atmosphere of Venus, this effect should be much stronger.

Direct measurements by spacecraft have established that the main component of the atmosphere of Venus is CO_2 [27]. At high temperatures and pressures, the spectrum of CO_2, as is true for other gases (H_2O, HCl, HF and CO), present in the atmosphere of the planet, shows a large number of transitions of thermally excited states and bands induced by pressure. If these bands cover all the "gaps" in the thermal spectrum of the atmosphere, a significant greenhouse effect arises; if this does not occur, however, the required effect is not present. All of these gases are transparent in the visible area of the spectrum and therefore can allow solar energy to penetrate to the bottom of the atmosphere to heat the "greenhouse." /57

However, in this "pure" form the model of the greenhouse effect encounters serious difficulties which Hunten and Goody [105] studied on the example of a model with a gray atmosphere under conditions of radiation equilibrium. Considering that in a sulfur atmosphere the position factor for the radiation of a planet is independent of frequency, they wrote the relationship of surface temperature T_s and optical thickness τ in the IR-area, using the Milne-Eddington approximation:

$$T^4_s = F(2 + \frac{3\tau}{2})/2\sigma,$$

where σ is Stephan's constant, F is the flux of departing radiation which, under conditions of equilibrium, can be assumed equal to the effective flux of solar radiation. To produce F, they averaged the incident radiation over the entire planet for day and night, considering that 77% of the incoming solar raidation is reflected back; as a result, $F = 1.6 \cdot 10^5$ erg/cm^2·sec. Then $\tau = 60$ for 600 K and $\tau = 113$ for 700 K. These values of τ for a purely gas medium are quite high (although not impossible).

However, the values of τ produced must in some manner be correlated to the presence of the continuous cloud cover in the atmosphere of Venus.

The problem is how to allow the input of energy to the layers of the atmosphere below the clouds when both these layers and the cloud layer are quite opaque.

The cloud cover of Venus is doubtless a very effective shield for the thermal radiation of the planet. Observations have shown that in the IR-spectrum of the radiation emitted by the planet there are virtually no bands or lines corresponding to the high temperatures obtaining below the cloud layer.

Thus, all or most of the IR-radiation is emitted by the clouds. The thermal pictures of the planet show no "hot spots," where the surface of the planet might be radiating through gaps in the cloud layer. Analysis of the visual albedo of the planet shows [[158] that the optical thickness for the clouds in the visible portion of the spectrum is $\sim$30; in the IR range, it should be $\sim$60. Due to this, the clouds should have an important role to play in radiation transfer [12] which, however, is difficult to determine due to our ignorance of the composition and structure of the cloud layer. /58

Let us now go over to analysis of the models of the greenhouse effect which have been constructed.

Strelkov [38] analyzed the transfer of radiant energy in the layers of the Venusian atmosphere below the clouds in the Schwarzwild-Schuster approximation. He assumed that the atmosphere of Venus is in local thermodynamic equilibrium, that transfer occurs as a result of absorption and reradiation, that the cloud layer fully absorbs radiation in the IR. Two cases were studied: 1) a gray atmosphere; 2) coefficient of absorption of the atmosphere in the 8-12 μ area significantly less than in the remaining IR-band. In both cases, the presence of the cloud cover is equivalent to only a slight decrease in the required optical depths.

Assuming that CO_2 makes up 5 and 15% of the total mass of the atmosphere of Venus, Strelkov estimated the content of water vapor

which, together with the concentrations of CO_2 used, could provide the required nontransparency of the atmosphere in the 8-12 μ band.

By the method of discrete ordinates, Samuelson [159] solved the problem of the thermal structure of a plane-parallel semi-infinite atmosphere, consisting of light-scattering particles and maintaining radiant equilibrium. The source of energy was solar radiation; in the visible and IR-areas, the atmosphere was gray. The scattering in decease as applicable to Venus were calculated by the theory of Mie; the distribution of particles by dimensions was considered flat.

One important result of the works of Samuelson [159, 160] is that within the framework of the theory of radiative equilibrium, it was found impossible to produce the required high surface temperatures: clouds of any acceptable composition would so strongly absorb and scatter the incident solar radiation that the maximum temperature at the equator would reach only 507 K. Further movement within the framework of this theory requires more detailed knowledge of the optical properties of the clouds or of their chemical composition, or measurements of the incident solar radiation flux, in order to produce the distribution of the incident radiant flux through the depth of the atmosphere.

In a number of works, Sagan and Pollack studied a model of the non-gray greenhouse effect in the atmosphere of Venus [145, 148].

Considering the high temperature below the cloud layer to be a reliably established fact, Pollack [145], based on the results of the direct measurements of Venera 4, assumed the components of the lower atmosphere of Venus to be CO_2 (main component), H_2O and N_2 (minor components). Considering the available estimates of the /59
temperature above and below the cloud layer, Pollack considers the clouds to consist of water; in the upper portion, they might contain crystals of ice, in the lower portion -- drops of water 7.5-10 μ is radius. The pressure at the top of the cloud layer is assumed to be 230 mb, the temperature 210 K; at the surface -- 75 atm and 700 K respectively.

Under these conditions, the absorption of solar radiation at various levels of the atmosphere was calculated considering absorption in the various bands of carbon dioxide, water vapor and nitrogen. Then, the flux of infrared radiation radiated by Venus is calculated. After this, the distribution of temperature in the lower atmosphere is constructed considering radiation in the microwave band. The calculations indicate that N_2 makes a slight contribution to the opaqueness for all of the models studied. The temperature gradiant below the cloud layer is almost universally

adiabatic, with the exception of the area near the base of the layer, where it decreases rapidly.

Only 0.5% water vapor is necessary for the required greenhouse effect. The temperature at the base of the cloud layer in this case is near the freezing point of water, and both H_2O and CO_2 make a significant contribution to the nontransparency in the microwave band.

In conclusion, a study is made of models of the greenhouse effect in the atmosphere of Venus based on absorption by CO_2 alone; absorption in the cloud layer; absorption by aerosols. The author concludes that satisfactory agreement with observations and the spacecraft data can be achieved only by the combined effect of absorption of CO_2 and H_2O in the cloud layer and the underlying atmosphere.

One important question for the mechanism of heating of the surface of Venus is the presence or absence of convection in the layer beneath the clouds. In radiant equilibrium, most of the increase in temperature with depth occurs with the lowest scale of altitudes of the absorbing material. Due to this, the greenhouse effect might result in an above-adiabatic temperature gradiant near the surface and convective instability [48]. Observations show that the temperature gradiant in the lower atmosphere is near adiabatic. Local thermal convection can transmit heat only upward; therefore, when there is convection the flux of solar energy penetrating to the lower atmosphere should be greater (with a given surface temperature) than without convection.

Calculations have shown [182] that when there is convection in order to reach a high temperature, higher opaqueness is required, although if opaqueness passes a certain limit, turbulent flow directed downward arises. However, it is also very difficult to produce a surface temperature over 500 K in a radiative-convective model. /60

Strelkov and Kukharskaya [42] have constructed a model of the greenhouse effect in the atmosphere of Venus based on the data measured by Venera 4, considering that the layers beneath the clouds are in convective equilibrium, and that turbulent exchange between the surface and the atmosphere on Venus is significantly greater than on Earth.

The authors came to the conclusion that with the values of the structural parameters measured by Venera 4, the lower atmosphere of Venus should be in the state of convective equilibrium. The adiabatic gradiant beneath the clouds would be established with a surface temperature of 750 K.

Studying the temperature mode of the surface of Venus, we must not ignore the transfer of radiation in the spectral ranges 3975-5125 and 5525-7025 cm^{-1}. At T>700 K, the energy lost by the surface in these "windows of transparency" corresponds to a significant fraction of the heat in the IR-area. On the other hand, the transfer of radiation in the "window" centered around 3.3 μ is insignificant.

In the opinion of the authors, the action of the greenhouse mechanism in the Venusian atmosphere is sufficient to provide heating of the surface to the required high temperatures. Kuz'min and Vetukhnovskaya reach a similar conclusion [19].

The difficulties encountered by the greenhouse hypothesis in explaining the heating of the surface to 600-800 K stimulated Newell [138] to doubt once more the existence of these high surface temperatures on Venus and to attempt to resurrect the ionospheric model. In his opinion, the ionospheric and microdischarge models can be reanalyzed considering the differences in conditions on the Earth and on Venus. Possibly polar auroras occur on Venus, accompanied by radio radiation. Venus might experience a glacial period (albedo 0.76) or might have temperatures similar to those on Earth.

Strelkov [39] has presented a critical discussion of the "ionospheric" model of the atmosphere of Venus, and of its "well" version.

One of the important parameters determining the heating of the atmosphere of Venus is the effectiveness ε of heating of the atmosphere by solar UV-radiation. The difficulties of determining ε by calculation stimulated Stewart and Hogan [177] to suggest an empirical method for determination of ε for the atmospheres of Mars and Venus. The method is based on the fact that the rate of decrease of electron density over the ionization maximum is a sensitive function of ε, while other parameters influence it only slightly. The distribution of electrons, according to the data of Mariner 4 and Venera 4, were compared with the theoretical curves /61 calculated for various values of ε. The best agreement for Venus was obtained at $\varepsilon = 0.27 \pm 0.08$.

Planetary Circulation and its Possible Role in the Heating Mechanism

The difference in mean insolation of the poles and the equator could generate horizontal temperature gradiants. Such conditions lead to instability, and the slow rotation of Venus might generate large-scale circulation of a sort reminiscent of Hadley

cells: the air rises over the tropics, moves to the poles, descends and returns to the tropics along the surface.

Calculations have shown that the movement of the atmosphere related to this convection could reach 30 m/sec in the upper boundary layers. The calculations were based on fairly unreliable data, but in any case show clearly that practically all horizontal temperature differences would be rapidly eliminated (observations confirm the absence of any significant temperature differences over the disc); furthermore, the deep flows, although very slow, might be adiabatic and generate an adiabatic temperature gradiant even without solar radiation influx. Possibly, it is deep circulation of this type which allows a full explanation of the high temperature of the surface of Venus.

This model does not consider circulation of the atmosphere (with return motion) at 100 m/sec (see Section 5, page 29 [original Russian page -- tr.]). Although data on this circulation are not extensive, its existence is beyond doubt. In this case, we must assume that in the atmosphere there are two independent dynamic solutions.

Model of the Atmosphere of Venus

Until the chemical composition and structural parameters of the lower atmosphere of Venus were established by direct measurements, models had to be based on data from radio observations and various indirect considerations.

As an example, we can note the work of Pollack and Sagan [147], dedicated to analysis of the measurements of Mariner 2 at λ = 19 mm on the assumption that the surface of Venus is hot. Five models of an absorbing cold atmosphere consisting of CO_2, N_2 and H_2O were studied; in two models, an aerosol which scattered or absorbed radiation was added. The models considering only nontransparency do not agree with the data of Mariner 2. If there is actually a low value of ε = 1.45 for radar studies at λ = 3.8 cm, /62 then the model with the isothermal absorbing cloud layer is correct. The upper limit of CO_2 at the surface is 16-150 atm, the concentration of H_2O is 640 g/cm^2. A significant gradiant of brightness temperature with longitude was observed, agreeing with the gradiant produced by the phase effect at λ = 3 and 10 cm.

However, if the low reflectivity of Venus at λ = 3.8 cm results from the attenuation of radio waves in the atmosphere, the explanation of the Mariner 2 data requires a model with a continuous absorbing agent plus an absorbing or scattering cloud layer. The most probable component of the layer is drops of liquid water.

The scattering model can be satisfied by dust, hail or large drops, but the diameter of the particles is ≤ 0.5 mm.

Vetukhovskaya and Kuz'min [7] suggested a two-layer model of the atmosphere for interpretation of the radar observations of Venus, satisfying the results of observations both of the natural radio radiation of Venus, and of the reflected radar data (including at 3 cm, where the effective reflection cross section of Venus is much less).

The upper "cold" absorbing layer determines the spectrum of the natural radio radiation of the planet, but is transparent for wave lengths in the radar frequency range. The lower "hot" layer, located near the surface of the planet, absorbs centimeter radiation and determines the frequency dependence of the effective reflection cross section of Venus, but does not influence the measured brightness temperature, since it is near the surface temperature. This might be the lower level of the clouds, containing $1-2 \cdot 10^3$ g/cm^2 dust or 3 g/cm^2 liquid aerosol (but not water).

Only after establishment of the composition of the lower atmosphere and its structural parameters did it become possible to construct reliable models of the atmosphere of Venus.

For example, in the works of Mikhnevich and Sokolov [25] and Avduyevskiy et al [1], models of the atmosphere of Venus were constructed considering the data of direct measurements of Venera 4 and the Mariner 5 radio occultation experiment. The results of determination of pressure on the Venera 4 spacecraft by the direct (aneroid) method agree well with the calculations of pressure over the path traveled; the agreement of the altitude distribution with the results of determination of pressure on Mariner 5 only if the relative zero altitude is shifted by $\sim$20 km [25].

The results of measurements of the Venera and Mariner 5 spacecraft have provided us with information on the pressure and temperature within limits of 0.08-27 atm and 240-600 K. Extrapolation of the measurement data downward toward the surface requires that we make some assumption concerning the course of the change in temperature with altitude. If we assume that the temperature changes adiabatically right down to the surface of the planet, the temperature produced is 670-800 K, the pressure 60-140 atm. /63

The mean temperature of the surface, according to radio measurements assuming an adiabatic atmosphere, is 700 $\pm$ 50 K. If the lower atmosphere contains some agent which absorbs solar radiation, the temperature gradiant may decrease to the point of appearance of an isothermal layer near the surface. Under these

conditions, the atmospheric model constructed from the data of measurements by the Venera spacecraft can be matched to the radio astronomy data at lower temperatures (∿650 K), but rather high pressures (∿100 atm) [6, 8].

13. The Cloud Layer

General Description of Observed Details

Venus is covered with a continuous, unbroken layer of clouds, opaque throughout the entire optical range. Breaks in the cloud layer, through which the surface of the planet might be observed, have never been seen. This so greatly contradicts the observed cloud formations on Earth, that at first glance it is impossible to see anything in common between the cloud cover of Earth and Venus. However, we must not forget the difference of the points of view: we observe Venus from an incomparably greater distance than Earth.

Jeffries [113] compared a photograph of Earth taken by Lunar Orbiter 1 with a photograph of Venus in the same phase. The cloud cover of Venus was found to be much more even, with no breaks, while the terminator on Earth was more irregular. The absence of any clearly expressed bandedness in the cloud layer of Venus is explained, in the opinion of the author, by the low Coriolis force resulting from the slow rotation of the planet. Although atmospheric circulation on Venus is quite possible, a result of the differences in temperature on the day and night sides, its influence on the structure of the atmosphere has not been seen.

The evenness of the cloud of Venus was also noted by Keene [117]. However, Keene believed that there might be small-scale irregularities in the cloud cover, so that if Venus were observed by a satellite at sufficiently close range, it might be possible to observe the surface through breaks in the clouds.

Polozhentseva [30] has compared the value of changes in violet absorption in the atmosphere of Venus determined by various authors in 1960-1964 to solar activity. This comparison indicated an inverse dependence on solar activity. The violet absorption is related to the presence of dark spots in the atmosphere of Venus. These spots have been found to vary inversely with solar activity, /64 on the basis of ∿300 photographs made at various observatories.

Grishin [15] noted that the "blue clouds," that is clouds absorbing solar radiation in short wave lengths, observed on Venus, the Earth and Mars might indicate similarity of these formations in the upper layers of the atmospheres of these planets.

Finally, Goody [94], using data on refraction in the layer above the clouds on Venus, produced by observation of Venus as it crossed the disc of the sun (refraction angle ~0,9 min) calculated the density of the atmosphere for the level of refraction. He produced $\rho = 0.007\text{-}0.013$ g/cm^3 ($p \simeq 7\text{-}13$ mb), depending on the composition of the atmosphere (the first numbers relate to an atmosphere of CO_2, the second -- of N_2). The spectrophotometric measurements of Belton, Hunten and Goody can be used to produce a value of density for the level of formation of the spectral lines ($T = 250$ K, $\rho = 0.1\text{-}0.2$ g/cm^3).

Considering the value of the scattering factor found from these same observations, Goody produced a scale of altitudes of 3.7 ± 0.3 km. This agrees with the results of Dolfus based on the elongation of the ends of the crescent and correspond more closely to light fog then condensed clouds.

Details of the Cloud Layer and Movement in the Upper Layers of the Atmosphere of Venus

Many attempts to determine the period of rotation of Venus on the basis of Doppler shifts in the spectrum of the planet have been unsuccessful. However, careful observation of the disc of the planet as long ago as the 1930's revealed clearly genuine details on the disc, which could be related to movements of the atmosphere of the planet.

The International Astronomical Union organized cooperative work of 8-10 observatories, photographing the disc of Venus and studying the dark and light spots on the disc. In March-August of 1962, some 300 good photographs were produced. Many series of photographs overlap, showing the evolution of the clouds over several days with intervals of a few hours. In recent years, excellent photographs have been produced by Herbig on the 120-inch Lick Observatory reflectory; quite useful work was performed by observers using the 107-cm instrument of the Pic-du-Midi Observatory. Observations using small instruments, for example the 25-cm telescope at Brazaville, have also been quite useful.

Using photographs produced at the observatory of Khar'kov University in January-May 1954, Starodubtseva [35] detected dark formations in UV, blue and green rays ($\lambda\lambda$ = 370, 440 and 527 mμ). /65
Dark spots were seen in UV 14 times, in blue light 3 times, in green light 2 times.

The contrast levels of the dark spots were as follows:

λ = 370 mμ	0.07-0.71,
440	0.05-0.45,

λ = 527 mμ 0.07-0.24,

with the contrast of the spots increasing toward the terminator.

In the opinion of Starodubtseva, these details relate to the atmosphere of the planet and indicate its great dynamic activity.

The measurements of Boyer and Camichel [60] using a large number of photographs of Venus taken in UV-rays at the Pic-du-Midi Observatory have indicated the presence of dark spots of constant configuration, similar to the arms of the letter V or Ψ. The sidereal period of rotation of the spots is 4.06 days, rotation retrograde. The period fluctuates between 3.6 and 4.5 days with a period of 104 ± 0.1 days.

Using a Fabri-Pero standard and a diffraction spectrograph at the focal plane of the 193-cm telescope of the Upper Provence Observatory, Guinote and Feissel [99] studied the spectrum of Venus in order to detect and measure its rate of rotation. The mean equatorial velocity of the atmospheric layers of Venus, responsible for the formation of the lines, is 103 ± 10 m/sec, corresponding to a period of rotation of 4.3 ± 0.4 (retrograde). It is assumed that the axis of rotation is perpendicular to the orbital plane of the planet.

Thus, the atmosphere of the planet, at the level which relates to these observations, rotates with a period of ∿4 days, corresponding to a linear velocity of ∿100 m/sec.

As yet, no satisfactory explanation has been given as to the nature of the dark spots observed in UV on Venus. Only recently, Swings [178] set forth the suggestion that the "darkness" of certain areas on the disc is caused by the presence of CO_2^+ absorption bands.

Optical Properties of the Cloud Layer [178]

Precise polarization measurements were begun by Liot and continued by his student Dolfus. In a recent work, Jerels used six color filters and performed measurements at phase angles of 28° to 120°. Like Liot, Jerels found that the cloud particles have diameters of a few microns. Deirmengan believes the particles to be dielectric, and estimates their diameter at ∿1 μ.

The absolute spectrum of Venus from 2.8-14 μ was determined in the laboratory of the moon and planets of Arizona University, with a resolution of ∿50, using a germanium bolometer cooled to 2 K. These results were confirmed by Murray et al (California Institute of Technology) in the 8-14 μ transparency window, but disa- /66

greed with the more varied measurements of Sinton and Strong, who found slightly greater surface brightness. It is still not known what property of the clouds creates the low brightness temperature in the 8-10 μ area and what mechanism accounts for the strong absorption of sunlight in the 3-5 μ area.

Role of the Cloud Layer

If the clouds are so important for the physics of the lower atmosphere of Venus, three questions must be answered before forward movement can be continued:

a) Do the clouds consist of dust or of condensed matter, and specifically of what?

b) The existence of clouds usually requires the existence of motion; motion requires sources of heat which, as we have seen, are defined by the clouds; what is the nature of this interaction?

c) The clouds interact with both solar and planetary radiation, and the solar radiation should be greatly attenuated before reaching the surface. Is there any significant flux of heat to the lower levels of the atmosphere to maintain the high surface temperature?

Unfortunately, answers to these question require much better knowledge of the cloud layer than we presently have; furthermore, a reliable answer can be given to many questions only by direct measurements in the cloud layer itself, which is a matter for the future. Due to the absence of direct and reliable data, our knowledge of the cloud layer is rather indefinite, and at times our information is contradictory.

We should note that if the clouds consist of dust, the dust might fill the entire atmosphere right down to the surface; if they consist of condensed matter, there might be a clear layer beneath the clouds.

The high temperatures and pressures at the surface would allow many vapors capable of condensation to exist. There might also be several layers of clouds of different compositions, one of which might be ice or water.

Ice Clouds. In order to confirm (or deny) the latter, two types of spectral observations could be used: a) the reflected cloud spectrum; b) the sharp lines of absorption of water vapor.

Ice clouds have broad absorption bands near 1.5 and 2 μ and are very slightly reflective at 2.7 μ. Spectra of Venus have been produced in this area by Kuiper and Forbes [119, 120] from an airplane and by Bottema et al [59] from a balloon. /67

The bands at 1.5 and 2 μ are difficult to detect due to the strong CO_2 absorption in the spectrum of Venus. However, Kuiper and Forbes, using their aircraft spectra, concluded that the depth of the lines is not over a few percent and that the clouds therefore do not consist of ice. Rea and O'Leary came to a similar conclusion [152].

Comparison of the reflection curves of the cloud layer of Venus in the 1.0-3.5 μ band with similar curves for the cirrus clouds and artificial ice clouds, as well as the absorption spectrum of CO_2, shows that there are no other absorption bands except the CO_2 bands. Therefore, clouds similar to our cirrus clouds with particle dimensions of ∿80 μ cannot exist on Venus. The presence of clouds with particles of submicron dimensions on the planetary scale is not probable. Therefore, ice is not the primary scattering element; however, no direct indications of what other element might be present are available. Incidentally, if the particles are very small in diameter, absorption will be very slight, and the question remains open.

On the other hand, Sagan and Pollack [157], using the modified Shuster-Schwartzwild approximation, presented expressions describing the monochromatic transmissive and reflective capacity, and also determined the absorption of the cloud layer.

The use of this formalism allowed them to produce a number of data on the cloud layer. The most probable component is ice. Liquid water, hydrocarbons and dust could not be the primary components of the upper portion of the cloud layer. The mean radius of the particles is 7.5-10 μ, the optical thickness is 18-43. A portion of the incident sunlight reaches the surface of Venus, but clouds with these properties are not transparent for the thermal radiation of the planet.

Balloon observations have shown that the planet is very slightly reflective in the 2.7-3.4 μ range (limit of observations). This condition is satisfied by CO_2, but an additional absorbent is required in the 3.0-3.3 μ range, for which ice would be quite suitable. Pollack and Sagan [157] have studied this fact as the strongest evidence in favor of ice clouds, although NH_4Cl is another suitable candidate.

Finally, O'Leary [139] made an attempt to detect a halo effect from ice crystals on the surface of Venus, which would cause the appearance of the well-known 22° halo.

The presence of ice crystals in the atmosphere of Venus would cause an increase in the shine of Venus due to the halo effect in comparison to the normal phase of the curve by 0.05^m at a phase angle of 157.5° and a decrease by 0.04^m at a phase angle of 159.4°. /68

Comparison of the theoretical curve with the observations at Kitt Peak Observatory indicated good agreement. The polarimetric measurments of Dolfus also show a maximum of polarization at a phase angle of 158°. CO_2 crystals do not produce this effect.

Data are available indicating that the upper portion of the cloud layer is a "fog," in which reflected solar rays travel a long, curved path. With the temperature of 240 K known from measurements, calculation of the maximum water vapor pressure shows that it might be in equilibrium with ice particles. Therefore, the prospects of finding water vapor lines either by measurements from balloons or under conditions of maximum Doppler shift are good.

Many terrestrial observations have indicated weak absorption; some observers have noted the variability of absorption, while others have observed nothing. However, even the greatest observed values (content 10^{-4}) are much less than would have to be assumed for ice clouds [178].

On 14 May and 11 June 1967, Kuiper and Forbes [120] produced spectra of Venus from a high-altitude aircraft using a combination of a heliostat with a 30-cm telescope and an interferometer.

The area studied showed strong water vapor bands at 1.5 and 1.9 μ, plus a weaker band at 1.13 μ. The suspended mean content of H_2O in the atmosphere of Venus, based on all spectra, is 0-2 μ. The depth of penetration into the atmosphere of Venus was estimated on the basis of the hot CO_2 bands to be down to the level of about 300 K. From this, the upper limit of the relative content of H_2O vapor is $(2.5\text{-}5)\cdot 10^{-7}$. Ice crystal absorption near 2 μ was not detected.

Welch and Rea [185] attempted to estimate the upper limit of the content of water in the atmosphere of Venus, considering the presence of traces of HCl in the atmosphere. Reacting with water, HCl decomposes, forming an acid, which should absorb long radio bands. On this basis, the authors produced an upper limit of H_2O 0.007 g/cm^2. However, 0.1-0.2 g/cm^2 are required to explain the observed radio radiation spectrum of Venus. Therefore, Welch and Rea concluded that clouds of drops of water could not cause the greenhouse effect. However, in a later work [186], they pointed out that their calculations in [185] are inapplicable for very small drops with radius $<<\lambda$.

Based on the theory of absorption of radio waves by small drops, Welch and Rea constructed curves of optical transparency as a function of wave length for various HCl contents of the solution. They found that the presence of HCl has little influence on

the curves; therefore, the earlier estimate is incorrect, but its refinement changes the numerical value very little. /69

Thus, the predicted content of water vapor in the atmosphere of Venus on the assumption of the existence of ice clouds has not been detected.

In connection with this, Ohring [140] spoke out against the water nature of the clouds of Venus. He pointed out that the concentrations of vapor over the clouds are actually much less than those required for saturation and condensation. However, he assumed constancy of the concentration of H_2O with altitude; if the concentration decreases with altitude at a rate similar to that observed in the upper troposphere of the Earth, the observed concentrations in the atmosphere of Venus above the clouds do not contradict the hypothesis that they are made of water.

It should also be noted that the measurements performed by the Venera spacecraft definitely indicated the presence of water vapor in the layer beneath the clouds. This speaks in favor of water clouds.

As a result, it must be acknowledged that the suggestion that the clouds are made of water (more precisely ice) has neither been confirmed nor contradicted [105].

Clouds of Other Chemical Composition. The presence of free HCl has stimulated studies of other transparent compounds of chlorine, and Lewis [124] suggested NH_4Cl as a possible component of the clouds.

He constructed a state diagram of an HCl-H_2O system for various partial pressures of the components [125]. The estimates produced correspond to a 25% concentration of aqueous HCl solution. The equilibrium temperatures are: at 80 mb -- 204 K, at 500 mb -- 214 K. Estimates of temperatures for the corresponding pressures are 240 and 250 K. This is significantly higher than the equilibrium temperatures; droplets of HCl should evaporate and could not form cloud particles. Ice is formed at HCl partial pressures and order of magnitude lower than those observed, and could not be included in the composition of the clouds. The particles of the clouds might consist of NH_4CL: the necessary quantity of ammonia is many orders of magnitude lower than of HCl. (The vertical mass of the clouds is $\sim$1 mg/cm, contradicting the observed optical thickness.) The excess HCl would cause the appearance of very slight quantities of NH_3 in the upper portion of the clouds. One peculiarity of NH_4Cl is that after it descends to the lower layers and dissociates into NH_3 and HCl, these compounds, rising upward, would once more form NH_4Cl.

The index of refraction of 1.64 agrees better with polarization measurements and the intensity of the light of the plane than the index of 1.33, characteristic for ice.

Recently, Kuiper spoke out in favor of $2H_2O \cdot FeCl_2$ as a possible component of the clouds [105].

Dust Clouds. The difficulties encountered in the search for a suitable condensing substance have led to the development of models of dust clouds. The primary difficulty is that of providing a mechanism to constantly maintain the dust. Falling of particles should be prevented by a turbulent flow directed upward [49]. The energy necessary for this should be supplied by continuous delivery of solar energy to the lower layers of the atmosphere. /70

Thus, we encounter once more the basic difficulty of the greenhouse model: provision of a sufficiently great flux of thermal energy into the lower layers of the atmosphere.

An attempt by Hansen and Matsushima [103] to get around this difficulty by assuming the presence of sources of energy related to the internal heat of the planet was also unsuccessful. With a flux of 100 erg/cm^2·sec (a value similar to that of Earth) and an optical thickness of $\sim 10^5$, the quantity of dust with particle dimensions of ~ 1 μ would correspond to 10 g/cm^2.

It is hardly probable that such a great quantity of dust can be maintained by turbulence generated by such a slight flux of heat.

16. The Upper Atmosphere and Ionosphere of Venus

The basic difficulty encountered in the construction of models of the upper atmosphere and ionosphere of Venus has long been the limited information available on its neutral atmosphere and magnetic field. At the present time, thanks to the direct measurements made by the Venera spacecraft, we know that the primary component of the upper atmosphere of Venus, as of the atmosphere as a whole, is carbon dioxide CO_2, possibly with a slight content of the inert gases and nitrogen. HCl, HF, CO, O_2 and water vapor, detected spectroscopically, are minor impurities and cannot play a significant role in the physical and chemical processes and the processes of ionization of the upper atmosphere. Therefore, the conditions in the upper atmosphere of Venus will be primarily defined by CO_2 and its ion CO_2^+.

One promising method of study of the upper atmosphere and ionosphere of Venus is the use of instruments installed on spacecraft. These include plasma probes, allowing direct measurement

of the concentration of charged particles in the surrounding medium; radio probing of the atmosphere of the planets from an artificial staellite, as well as the study of propagation of radio waves between the Earth and the spacecraft, as the radio waves pass through the atmosphere and ionosphere of the planet (particularly during occultation of the spacecraft by the planet).

The use of probes yields information on the charged components of the upper atmosphere of the planets; the method of radio transmission allows information to be produced concerning the neutral component of the atmosphere as well (if we know the chemical composition). /71

The principle of the method of radio occultation is based on the fact that when radio waves enter the atmosphere or ionosphere of a planet, their propagation velocity changes in comparison with their velocity in interplanetary space, since the indices of refraction of the neutral and ionized components are not equal to 1.

Furthermore, the presence of a gradiant of the index of refraction with altitude causes refraction of the radio waves. If the proper wave length is selected, a significant change in the phase path is achieved; the influence of the interplanetary medium and the atmosphere of the Earth must also be considered. Finally, the results of the observations can be used, under certain assumptions, to construct an altitude profile of the index of refraction in the atmosphere of the planet. Then, in the area of altitudes where the index of refraction $n<1$, the altitude course of electron concentration can be constructed. In the lower portion of the atmosphere $n>1$; it is used to determine the characteristics of the neutral atmosphere of the planet. In particular, if we know the composition of the neutral component, we can calculate the distribution of the concentration of charged particles with altitude and then, using the scale of altitudes, construct the distribution of pressure and temperature with altitude.

It should be noted that the contributions of neutral and charged particles to the change in the index of refraction are opposite in sign.

Due to this, as we observe radio occultation at one frequency, the influence of these components cannot be separated, and we must assume that there are no charged particles in the lower atmosphere.

The use of two frequencies allows us to consider the influence of charged particles: it is easy to separate the contribution of the ionosphere to the measured phase increment. The high frequency used is generally a multiple of the low frequency [13].

Phinney and Anderson [143] indicated a curious analogy between the problem of determination of the altitude profile of the index of refraction of a radio beam in the atmosphere of a planet and the problem of determination of the change in velocity of a seismic wave based on the measured time of transmission. They also noted that in the case of a thin atmosphere, the solution is unique.

An experiment involving study of the upper atmosphere and ionosphere of Venus by radio occultation methods was undertaken on the Mariner 5 spacecraft.

Mariner 5 carried two transmitters, radiating at 49.8 and 423.3 MGz [180] and one transmitter radiating at ∿2298 MHz [118]. /72
A two-frequency experiment allowed the altitude profile of electron concentration in the day and night ionosphere of Venus to be determined. The experiment at 2298 MHz allowed an altitude profile of electron concentration in the day ionosphere of Venus to be produced; the apparatus was found to be insufficiently sensitive to measure the electron concentration in the night ionosphere.

Using the results of the Mariner 5 and Venera 4 measurements, McElroy [128] constructed a model of the upper atmosphere of Venus considering the photochemistry of CO_2.

The recombination of CO and O into CO_2 by triple collisions is extremely slow; the primary role is played by the formation of the excited molecule CO_3* which, reacting with CO, yields two molecules of CO_2. The rates of these reactions were estimated. On this basis, a thermal model of the atmosphere above the arbitrary level of formation of the lines was produced. The low and constant temperature gradiant [2°/km) and the constant scale of altitudes (5 km) to the 50 km level above the arbitrary level [sic. -- tr.]. There are two temperature minimums in the mesosphere at 50 and 70 km above the arbitrary level. The temperature of the exosphere is ∿700 K. Dissociative recombination of CO_2^+ might be a significant source of the sky glow of Venus in the fourth positive system of CO bands; it can be identified with the weak glow in UV detected by Mariner 5. The presence of a sufficient quantity of protons in the ionosphere might be explained by ionization on the night side (by diffusion). The lower (in comparison with Earth) temperature of the thermosphere of Venus is explained by the thermostating influence of CO_2, which is abundant on Venus.

Thus, a CO_2 atmosphere remains undissociated up to high altitudes [105]. This same unexpected result was also produced for Mars.

Under terrestrial conditions, CO_2 is easily dissociated, as a result of which atomic oxygen begins to predominate at altitudes of ~90 km. Under the conditions of Venus, CO_2 should dissociate into CO and O_2, the rate of this process being approximately equal to the rate of dissociation of O_2 on Earth. Due to this, we should detect an area on Venus where CO_2 is replaced by CO and O. However, there is no such area, and as yet there is no solution to this curiosity.

Shimizu [168] suggested various mechanisms of recombination of CO and O to explain the absence of O in the upper atmosphere of Venus:

$$\begin{aligned} CO + O(^3p) &\rightleftarrows CO_2^*, \\ CO_2^* + M &\rightarrow CO_2 + M, \\ O(^1D) + CO_2 &\rightleftarrows CO_3^*, \\ CO_3^* + CO &\rightarrow CO_2 + CO_2 \end{aligned}$$

/73

The recombination of excited molecules could occur rapidly with the participation of hydrogen-containing radicals; however, no quantitative estimates were presented. The detection of metastable molecules of CO_3 requires direct mass-spectrometric studies of the neutral gases and positive ions of the atmosphere of Venus.

Later, Shimizu [169] calculated the distribution of neutral and ionized components of the atmosphere of Venus with height considering dissociation and ionization by the short-wave radiation of the sun, aeronomic reactions, molecular, turbulent and ambipolar diffusion.

The chemical composition and temperature of the atmosphere at the lower boundary of the upper atmosphere and the temperature of the exosphere are assigned. Eleven models were calculated, consisting of CO_2 and N_2 with variable composition, as well as changes in the height of the sun, flux of solar radiation, high density of the atmosphere at the lower level, etc.

Since radiation in the Schuman-Runge continuum can penetrate deeper into the atmosphere of Venus than into that of Earth, the dynamics of the lower atmosphere will have a stronger influence on the upper atmosphere than on Earth. Comparison with Mariner 5 data indicates a deficiency of oxygen in comparison to the calculated value (by 2 orders of magnitude) at altitudes of 250-500 km. This can be explained by dynamic effects; the coefficient of turbulent diffusion is estimated as $(1\text{-}3)\cdot 10^7$ cm^2/sec (or a wind speed of 100-300 m/sec).

Continuing the work on the investigation of the upper atmospheres of the planets, Shimizu theoretically studied the upper atmospheres of Venus, Mars and Jupiter [167]. Based on models of

the atmospheres suggested by specialists of the jet propulsion laboratory in 1962-1965, he studied the atomic and molecular processes in the upper atmospheres of Venus, Mars and Jupiter. The determining processes for Venus and Mars are the dissociation of CO_2 and CO with the formation of O_2; for Jupiter -- ionization of H_2 with subsequent formation of atomic hydrogen.

The results of observations of Venus by Mensel and Voculer are widely used in the literature. This makes particularly important the reanalysis of the results of this work undertaken by Hunten and McElroy [106]. Critically analyzing the work of Mensel and Voculer, the authors concluded that the error in the scale of altitudes found by Mensel and Voculer H = 6.8 km is much greater than the value of ±0.2 km which they reported. The photometric curve which they produced also satisfies a value of H = 4.4 km. /74

According to the evaluation of Hunten and McElroy, at a distance of 6169 km from the center, the concentration of molecules is $3.2 \cdot 10^{13}$ cm^{-3}.

Ionosphere

The concentration of charged particles in the ionosphere of Venus has been measured using flat and hemispherical three-electron charged-particle traps [14].

The flat traps were designed for measurement of the concentration of ions in the peripheral portions of the ionosphere of Venus. In order to separate ions of ionospheric and nonionospheric origin, a positive voltage was periodically fed to one of the grids of the flat trap, slowing the thermal ionospheric ions.

Measurements on the flat traps were performed approximately each 150 km and allowed the concentration of particles to be recorded within limits of 50-5000 cm^{-3}.

The hemispherical traps were designed to measure positive ions near the main maximum. Since at the time when Venera 4 was launched the hypothesis of the possibility of a very high electron concentration (up to $10^9 cm^{-3}$) in the ionosphere of Venus was still popular, the sensitivity of the hemispherical traps was selected as 10^4-$10^7 cm^{-3}$.

Measurement using the hemispherical traps showed that in the night ionosphere the concentration of ions was never over $5 \cdot 10^4$ cm^{-3}. Measurements of low concentrations of ions allowed the upper limit of ion concentration to be established at $\sim 10^3$ cm^{-3} for altitudes over 300 km.

In the day ionosphere according to the data of Mariner 5 [118, 180], the maximum electron concentration is $5 \div 6 \cdot 10^5$ cm^{-3} at $\sim$140 km over the surface of the planet. There is an additional maximum at an altitude of $\sim$15 km below the main maximum. The scale of altitudes above the main maximum is $\sim$13 km, yielding a temperature of $\sim$300 K, if the main ion is CO_2^+. The scale of altitudes increases with increasing altitude, which means either an increase in temperature or a decrease in the mass of the ions, with light ions beginning to predominate, or possibly both at once.

Based on the data of the measurements of Venera 4 and Mariner 5, McElroy and Stroble [130] constructed a number of models of the night ionosphere, of which they themselves consider two to be most probable. In the first model, the upper portion of the ionosphere contains He^+ or H_2^+ ions, allowing the entire ionospheric profile to be explained. The second assumes ionization in situ upon collision of low-energy protons or electrons. The He^+ or H_2^+ ions probably enter from the night side as a result of lateral transfer. It is difficult to find the necessary flux of charged particles required by the second hypothesis. /75

McElroy suggests the following reaction as the main mechanism of maintainence of ionization of the day ionosphere [128]:

$$CO_2 + h\nu \rightarrow CO_2^+ + e \rightarrow CO + O.$$

Interpretation of the results of measurement of the electron concentration profile in the day ionosphere of Venus is facilitated by the fact that atomic oxygen has not been detected in the upper atmosphere of Venus. Therefore, it can be expected that the maximum of ionization will follow the rules of photochemical equilibrium and therefore can be described by a model similar to the terrestrial F_1 or D layers [13].

Explanation of night ionization is more difficult. The nightly maximum of ionization of Venus might be similar to the D or E layers in the night ionosphere of the Earth. The sources of ionization might be either solar radiation, if recombination of the day ionosphere is slow enough, or sources of night ionization [130]. The first source cannot be effective, since the time of recombination at the altitude of the maximum of ionization is $\sim$100-200 sec. Such sources as cosmic rays, meteorites and radiation scattered by neutral hydrogen, would yield a maximum of ionization at either a lower or a higher altitude than that at which it is observed. The most acceptable mechanism is transfer of charged particles from the day side to the night side by winds arising due to horizontal gradiants of temperature and consequently of pressure. However, the required wind speed is supersonic.

The problem of the night ionization of Venus still requires solution; possibly, fluxes of charged particles play a role here.

At great altitudes, 6800-750 km, the form of the night profile of electron concentration can be described by the distribution at 600-1100 K. In the 6300-6800 km area, the most suitable ion is He^+ at T = 620-970 K, at lower altitudes -- heavier ions [130].

The content of helium in the atmosphere of Venus should be much greater than its content in the atmosphere of Earth. This causes no particular difficulty, since Venus, due to the lack of any magnetic field, does not have the helium-loss source of the flux of light ions through non-closed force lines of the tail of the magnetosphere into interplanetary space, as does Earth.

In earlier years, before the flight of the Venera spacecraft, the hypothesis of a "well" ionosphere, suggested by a number of authors, was quite popular. Looking at this hypothesis critically, Strelkov [39] showed that the well ionosphere model fails to /76
explain the presence of radar reflections from the edges of the disc of the planet and the strong reflection from the center of the disc. The production of reliable direct data on the composition of the atmosphere of Venus and physical conditions on the planet fully "closed" this hypothesis.

Exosphere

Hogan and Stewart estimated the temperature of the exosphere of Venus on the basis of the scattering of solar UV-radiation [102]; for Venus, they produced, for ε from 0.19-0.35 T_{ex}, figures of 517-718 K.

Other estimates of the temperature of the exosphere are as follows (in K): 708 (McElroy), 700 ± 100 (Stewart); 680 ± 50 (Bart). This last value is based on the model of the mixture of H and H_2 set forth by Bart to explain the observations of radiation made by Mariner 5.

15. Evolution of the Atmosphere

The surprising difference between the atmospheres of Venus and Earth, two planets similar in mass, clearly of common origin and not too different in distance from the sun, has set forth the problem of explanation of the very great differences in the atmospheres of Venus and Earth by differences in the course of the evolution of their primary atmospheres. The most interesting works in this direction have been written by academician Vinogradov and his colleagues [10,11].

Comparison of the contemporary atmospheres of Venus and Earth indicates that the total quantity of degassed products for both planets is the same (with an accuracy to half an order of magnitude), with the exception of the hydrogen lost by Venus.

In the crust of the Earth, carbon is bonded to the carbonates of the sedimentary rocks and amounts to $\sim 2 \cdot 10^{23}$ g. If all the CO_2 from the carbonates and hydrosphere of the Earth were liberated into the atmosphere, its mass ($5 \cdot 10^{21}$ g) would be increased by $\sim$40 times, and the pressure would become 40 atm, similar to the pressure of the atmosphere on Venus.

This speaks in favor of the similarity of the endogenous processes on Venus and Earth (that is melting of the substances of the crust and processes of degassing of the interior), which occur approximately the same on planets of equal dimensions. However, the subsequent history of the atmospheres depends essentially on exogenous factors, primarily the distance to the sun and the mass of the planet, which determine the dissipation of the atmosphere.

Venus is closer to the sun, and its equilibrium temperature is over 50° C. This has resulted in strong conversion of H_2O and CO_2 in the atmosphere. In turn, this led to the creation of a powerful greenhouse effect, on the one hand, and significant photo dissociation of CO_2 and H_2O by the UV-radiation of the sun. The /77
oxygen formed was absorbed by the rocks of the surface of Venus, the CO (product of photodissociation of CO_2) was not conserved, and recombined into CO_2; the oxygen required was supplied by photodissociation of water. Under these conditions, the hydrogen easily dissipated. When the temperature of the surface reached 200-300° C, many carbonates reacted with silicates in reactions such as

$$MgCO_3 + SiO_2 \rightarrow MgSiO_3 + CO_2,$$

$$2MgCO_3 + SiO_2 \rightarrow MgSiO_3 + 2CO_2 \text{ etc.}$$

These reactions delivered a tremendous quantity of CO_2 to the atmosphere.

As a result, a thick atmosphere developed on Venus. Under these conditions, the surface rocks of Venus should have been subjected to deep rupture, which, probably, caused leveling of the surface of the planet.

Studying the course of evolution of the atmosphere of Venus, Dayhoff et al [77] noted that, due to the high temperature, the chemical processes in the atmosphere of Venus are determined by the tendency toward thermodynamic equilibrium.

Estimating the possible atomic composition of the matter of Venus on the basis of spectroscopic data, the authors have calcu-

lated the equilibrium composition of the atmosphere and come to the following conclusions:

a) There is practically no free carbon, hydrocarbons, formaldehyde or other organic molecules in the atmosphere of the planet;

b) There was more hydrogen in the primordial atmosphere of Venus, and at that time $C/O \leq 0.5$ (now $C/O \approx 0.5$);

c) Powerful wind erosion occurs, uncovering "fresh" rock, which bonds oxygen.

Shimizu and Urabe [170] studied the distribution of H_2O and CO_2 between the atmosphere, hydrosphere and lithosphere for terrestrial-type planets, based on a model of a gray atmosphere and the energy balance at the surface. They studied the state diagram of the trinary system H-O-C (nitrogen considered inert). Due to the absorption of IR-radiation by H_2O and CO_2, there is a critical level of incoming energy flux, above and below which high (<400 K) and low (<270 K) equilibrium surface temperatures are established. The high temperatures are stable, the low temperatures are quasi-stable.

Application of this method to the Earth and Venus shows that the atmosphere of Venus never contained much H_2O in the past.

Finally, Palm [142] has studied the relationship of the course of evolution of terrestrial-group planets to their distances from the sun and constructed a model explaining the presence of /78 a dense CO_2 atmosphere on Venus. It was formed by degassing from the interior of the planet, passing through three stages: 1) liberation of gases similar to terrestrial volcanic gases; 2) their interaction with the lithosphere, forming oxides and carbonates; 3) a drop in degassing and exhaustion of the water vapor by photodissociation, oxidation and hydration of minerals. The low CO_2 and H_2O partial pressures produced increased decarbonation, which generated the atmosphere observed.

16. Surface Details

During the radar observations of Venus in 1962, a detail was observed in the spectra of continuous signals, which continued its existence for several weeks and changed slowly from day to day [28]. During the observations of 1964, several similar details in the spectra were observed. It is highly probable that these details are caused by the structure of the surface of Venus, not by any atmospheric or ionospheric phenomenon. This is indicated primarily by the narrow band of frequencies of the details. However, the most convincing argument in favor of the theory that the spectral details correspond to singularities of the surface of the planet is their movement across the spectrum in full agreement with the assumed motion of surface details due to rotation of the planet.

Later, the existence of stable surface details on Venus was confirmed by many radar observations. For example, Aleksandrov, Zyatitskiy and Rzhiga [2] studied the Doppler spectrum of Venus in detail using the observations of 1964 by means of harmonic analysis with computers. The peaks observed in the reflection spectrum were identified with local surface areas with increased reflectivity. According to their estimates, one area extended 1200 km along a meridian and was not over 300 km wide.

We should note that as yet it is impossible to determine the nature of the surface producing these spectral details unambiguously. These details might appear if there are: 1) areas with greater than average dielectric constants; 2) areas which are more uneven than the surrounding surface, an area with radius of curvature of surface irregularities comparable to the wave length; 3) highly uneven areas with radius of curvature significantly greater than the wave length, so that multiple reflections are possible. These surface details can be arbitrarily called "mountains" [93], since their strong reflectivity and depolarization of the incident radiation are reminiscent of the properties of mountain areas; however, they might also be craters or fields of boulders, or geological formations like the Grand Canyon. /79

Due to the rotation of the planet, various areas pass through the center of the disc, allowing us to study variations in reflectivity of the surface of Venus in the equatorial zone; as a rule, these variations do not exceed 2 times. Estimates of the angle of inclination of the surface, produced on the basis of the reflectivity of the surface of Venus, show that the most probable value of slope angles is $\sim 3°$. Variations in radius on Venus do not exceed 5 km [164].

The development of the method of radar interferometry allowed scientists to begin constructing rather detailed maps of the reflectivity of the surface of Venus [149, 150]. This work was performed, in particular, in 1968-1969 by the Lincoln Laboratory. The result was a radar map of the surface of Venus at $\lambda = 3.8$ cm [93]. The work was conducted using 2 antennae 36.5 and 18.3 m in diameter; the separation between the antennae was 1200 m. The 350 kw signal radiated by the larger antenna had right circular polarization. The reflected signal with left circular polarization was received by both antennae, and its frequency analyzed with a resolution of 1 Hz, allowing the surface of the planet to be separated into "Doppler bands" and "circles of equal distances." The resolution on the surface of the planet was ~ 150 km. The signals received by both antennae were multiplied, which determined the amplitude and phase of the "interference bands." The signals were callibrated every 15 seconds on the basis of the echo from the subterral point (point closest to the radar) on the planet in order to eliminate the influence of irregularities in the atmos-

phere of the Earth. The interference band picture allowed two points with equal distance and Doppler shift to be separated, thus avoiding ambiguity in the construction of the map.

The map constructed revealed many new details of the surface and improved the position and structure of details observed earlier. It is noteworthy that Venus has large circular regions with significantly lower reflectivity than the surrounding terrain.

The largest details on the surface were initially marked α, β and γ. Form β is near circular with a diameter of $\sim$250 km. 1000 km to the north of β is area δ, of approximately the same size. These are regions of increased depolarization, indicating significant irregularity of the surface.

Later, the fine structure of detail β was revealed [188]. It consists of three spots with the coordinates

+26°	+32°	+35°
-34°	-40°	-32°

/80

The longitude λ is red from the central meridian intersecting the subterral point at the moment of the inferior conjunction of 1967.

The Question of Ice Caps on Venus. In 1968, Libby [126], explaining the acute shortage of water in the atmosphere of Venus, set forth a suggestion that the primary mass of water on Venus might be concentrated in the form of ice caps at the poles of the planet, where he felt it was quite possible that rather low temperatures and even life might be present. This hypothesis was criticized by Weertman [184], who noted that if we assume the quantity of water on Venus to equal to that on Earth, the ice caps of Venus would be too large, reaching a thickness of 47 km. We might note that the search for a temperature gradiant from the equator of Venus toward its poles has been fruitless [79, 90], which also makes the suggestion of Libby doubtful [81].

17. Life

In the opinion of Sagan [156], the high surface temperature practically eliminates the possiblity of the existence of life forms on the surface of Venus. However, Sagan himself, together with Morovits, has set forth a purely speculative hypothesis [133] of the possibility of existence of an exotic form of life in the form of hydrogen-filled bubbles, in the lower portion of the cloud layer, where the temperature is $\sim$300 K.

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